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Impact of Ozone and Sulfur Dioxide on the Yield of Agricultural Crops

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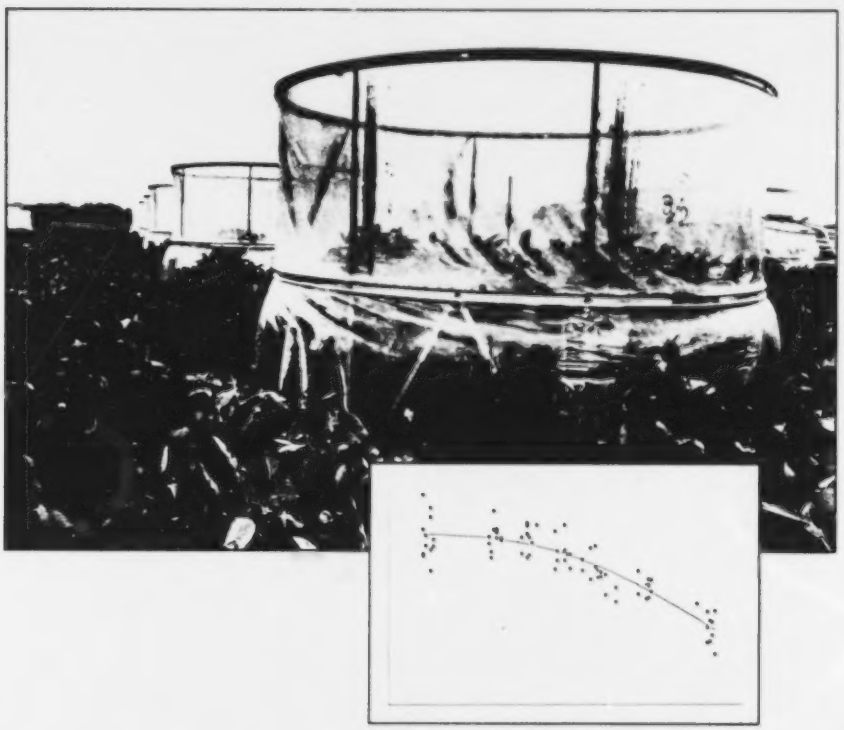

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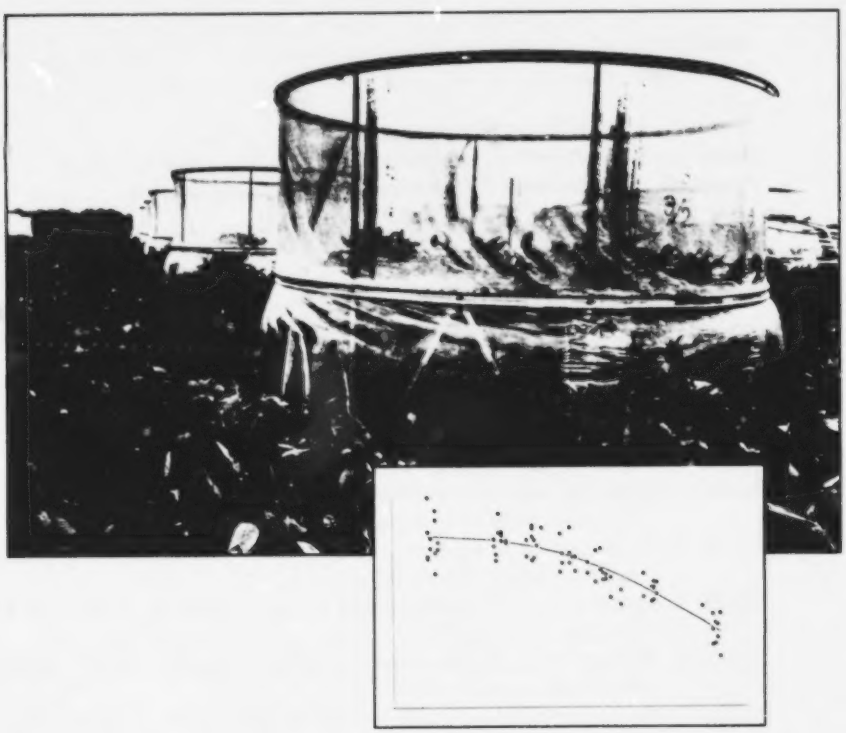

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Impact of Ozone and Sulfur Dioxide on the Yield of Agricultural Crops

M. C. Sommerville, Assistant Statistician
S. E. Spruill, Assistant Statistician
J. O. Rawlings, Professor
V. M. Lesser, Assistant Statistician

Department of Statistics
North Carolina State University

Contact author: S. E. Spruill, 1509 Varsity Drive
Box 8203, North Carolina State University
Raleigh, North Carolina 27695-8203

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16. ABSTRACT

The National Crop Loss Assessment Network (NCLAN) was formed in 1980 to assess the effects of air pollutants on major agricultural crop yields. NCLAN consisted of U. S. government and non-government organizations that conducted field experiments, crop yield modeling, and economic analyses. Ozone (O_3) and sulfur dioxide were selected as the air pollutant treatments for NCLAN studies because they were known to cause damage to vegetation. Experimental methods and results from individual studies have been reported by the principal investigators in many publications.

In 1984 a centralized database management system was formed at North Carolina State University, Raleigh, NC. Data from each project were documented and archived in the library.

The purpose of this publication is to summarize the statistical methods used in the combined analyses, to present the polynomial and Weibull O_3 dose-response equations determined in the combined analyses, and to summarize the effects of O_3 on crop yields by presenting estimated relative yield losses for postulated levels of O_3 pollution.

17. KEY WORDS AND DOCUMENT ANALYSIS

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IMPACT OF OZONE AND SULFUR DIOXIDE ON THE YIELD OF AGRICULTURAL CROPS

INTRODUCTION

The National Crop Loss Assessment Network (NCLAN) was formed in 1980 to assess the effects of air pollutants on major agricultural crop yields. NCLAN consisted of U.S. government and non-government organizations that conducted field experiments, crop yield modeling, and economic analyses (Heck et. al. 1982, Heck et. al. 1984). O_3 and sulfur dioxide were selected as the air pollutant treatments for NCLAN studies because they were known to cause damage to vegetation. Field experiments utilized open-top chambers (Heagle et.al, 1973) in an effort to simulate natural field conditions and simultaneously control exposures of known pollutant concentrations. From 1980 through 1986, NCLAN completed a total of 41 studies on 14 crops. Experimental methods and results from the individual studies have been reported by the principal investigators in many publications (e.g., Heagle et al. 1983, Heggestad et al. 1985, Kohut and Laurence 1983, Kress and Miller 1983, and Temple et al. 1985). Detailed information on NCLAN's history, methods, and results may be found in Preston and Tingey (1988), Heagle et al. (1988), Rawlings et al. (1988), and Adams et al. (1988).

In 1984 a centralized database management system (the NCLAN Data Library) was formed at North Carolina State University, Raleigh, N. C. Data from each project were documented and archived in the Library. Statistical analyses combining the information over studies for each crop were conducted using the Library database. Following detailed analyses of the behavior of the residuals, the effects of O_3 on crop yields were summarized in terms of O_3 dose-response equations and estimated relative yield losses (RYL) for subsets of studies showing homogeneous response to O_3. In addition, overall "average" O_3 dose-response equations were determined for each crop even though responses to O_3 may not have been homogeneous. Both polynomial and Weibull response models were used.

The purpose of this publication is to summarize the statistical methods used in the combined analyses, to present the polynomial and Weibull O_3 dose-response equations determined in the combined analyses, and to summarize the effects of O_3 on crop yields by presenting estimated relative yield losses for postulated levels of O_3 pollution.

MATERIALS AND METHODS

Description of Experiments

NCLAN investigated the effects of O_3 on 14 crops with the emphasis on corn, cotton, soybean, and wheat. Eight crops were represented by more than one cultivar and nine crops were studied in more than one environment (site and/or year). All studies included multiple levels of O_3; in addition, 12 studies included levels of sulfur dioxide (SO_2) and 14 studies included soil moisture stress treatments. Open-top chambers were used in all studies to control air pollution levels in the plant canopy (Heagle et al. 1973). Site and year codes and other abbreviations used in all tables are summarized in Table 1. Key features of the individual experiments are given in Table 2. The reader is referred to Heagle et al. (1988) and to publications of the principal investigators (Appendix A) for more details of the individual experiments. The principal investigators are listed in the footnote of Table 2.

The basic NCLAN protocol was the same for all sites but experimental designs and O_3 dose levels of the pollutants varied from study to study. The experimental designs included completely random designs, randomized complete block designs, and single replicates of 2-factor factorials. In all cases, levels of O_3, SO_2, moisture stress, or combinations of these factors were whole-plot treatments. Each open-top chamber constituted a whole-plot experimental unit. Cultivars, when a treatment factor, were used as sub-plot treatments. The O_3 and SO_2 treatments were expressed as levels of pollutant realized from charcoal filtering (CF), ambient air (AA), and from additions of specified amounts of pollutant to ambient air during the exposure time period (7 or 12 h) of each day. Earlier NCLAN studies used specified constant additions of O_3 during the exposure period; later studies used proportional increases in O_3 over ambient levels.

Early NCLAN studies used 7 h daily exposure periods. In general, NCLAN adopted a 12 h daily exposure protocol in 1984 after Heagle et al. (1987) showed an important effect of the additional 5 h of daily exposure. The O_3 dose for each plot was summarized in terms of the seasonal average of the monitored levels of O_3 during the 7 h , or 12 h , daily exposure time period. Because of occasional equipment failure and, in some cases, nonmonitoring on weekends, some studies had missing O_3 monitoring data. Missing values were replaced, according to the protocol described in Appendix B, before the seasonal O_3 means were computed. For the combined statistical analyses, all 7 h seasonal O_3 dose metrics for a particular crop were converted to 12 h metrics, according to the protocol given in Appendix C, if one or more of the individual studies used 12 h exposure periods. The studies conducted as 7 h exposure studies can be identified in Table 3 as all those showing a 7 h metric plus those

with a converted (as indicated by the footnote) 12 h metric. Since the studies were not designed for interspecies comparisons, O_3 dose metrics were not standardized across all species.

Statistical Analyses

Failure to precisely meet the targeted additions of O_3 caused slight differences in realized levels of O_3 among replicates of the same treatment. This introduces a slight imbalance within each data set that causes the conventional analysis of variance for each experiment, which assumes all replicates of a given treatment received the same O_3 dose, to be only approximately correct. In addition, differences in experimental designs, treatment factors, and levels of the treatment factors over experiments invalidated the conventional analysis of variance methods for combining data. Therefore, all analyses of combined data used regression methods in which the levels of O_3 and SO_2 were treated as continuous variables. For all O_3 dose-response equations, the dependent variable was yield (in kg ha^{-1} except for barley) or transformations of yield. The independent variables were seasonal arithmetic means of O_3 ($\mu L\ L^{-1}$) and seasonal means or sums of SO_2 ($\mu L\ L^{-1}$ or $\mu L\ h\ L^{-1}$) computed over the periods of exposure to the pollutants. All models included effects to account for site, year, replicate, cultivar, and moisture stress effects. Other variables, such as initial growth and companion plot yields, were used as potential covariates.

The coordinated statistical analysis of the NCLAN data proceeded in three somewhat distinct steps. The first was analysis of the behavior of the residuals for each crop to detect outliers and to investigate the validity of the least squares assumptions of homogeneous variance and normality. Depending on the results from the residuals analyses, decisions were made as to whether unweighted or weighted least squares and/or transformations should be used for the subsequent analyses. The second stage was the fitting of O_3 dose-response models with the primary objective of quantifying the effect of O_3 on crop yields taking into account the interacting effects, if any, of cultivars, SO_2, and moisture stress when NCLAN data provided information on these factors. Finally, the O_3 dose-response equations were used to estimate the yield losses that would be incurred, relative to the yield at $O_3 = 0.025\ \mu L\ L^{-1}$, under postulated seasonal (7 h or 12 h) mean levels of O_3. The estimated relative yield losses (RYL) are presented in terms of their 95% confidence interval estimates.

Residuals Analysis

The residuals analysis used the combined data for each crop to detect outliers, to investigate the validity of the least squares assumptions of homogeneous variance and normality, and to determine whether weighted least squares and/or appropriate

transformations of the response variable would be desirable. Prior to the residuals analysis, the data were standardized over experiments for a given crop in the following manner:

(1) Yields were converted to units of kg ha^{-1} in all cases except barley for which stand density information was not available.

(2) The size and orientation of plots were standardized for each crop, to the extent possible, to minimize the effects of plot size and shape on variances.

In all studies, the whole plot was the 3 m diameter open top exposure chamber (Heagle et al. 1973). Most studies recorded data by one-meter row segments with a total of four one-meter row segments per chambered plot. The subplot size for the split-plot study with the largest number of cultivars (the subplot treatment) determined the size for the standardized plots for the crop. Plot sizes were then standardized for all studies involving that crop by subdividing the data for each study into appropriate combinations of one-meter row segments. Attempts were made to maintain north-south orientation of the standardized plots across experiments when plot data were subdivided. These "standardized" data sets were used only for the analysis of residuals.

Appropriate analyses of variance were run for each study. The residuals from each analysis were inspected for outliers and any obvious violations of the least squares assumptions, and then pooled for the combined analysis of residuals. Any residual larger in absolute value than twice the root mean square error was tentatively considered an outlier. These data values were referred to the proper principal investigator for verification. While some observations had been deleted from the original datasets by the principal investigators, no additional observations were removed as a result of the residual analyses. Normality and homogeneity of variance were judged by patterns in the normal plots and plots of the residuals against predicted values and treatment levels (Rawlings, 1988, pp. 253-265). In those cases where a single replicate of a factorial set of treatments was used, the residuals from the "best fitting" polynomial response equation were used.

Homogeneity of variance within studies , among studies within sites, and between sites as applicable was tested with Bartlett's chi-squared test of homogeneity (Steel and Torrie, 1980, pp. 471-472). Results from these tests were used in conjunction with residuals plots to assess the validity of the assumption of constant variance. When heterogeneity of variance was detected (α=0.05), the data were reanalyzed using weighted analyses of variance wherein the observations were weighted by the inverse of the error variances obtained from the individual (unweighted) analyses of variance or from pooled estimates of variance, pooled over subsets of data not showing significant heterogeneity. If the weighted least squares analyses satisfactorily eliminated the variance heterogeneity, it was assumed that the observed

heterogeneity resulted from the differences in variability among sites and/or years. If the results from the weighted analysis continued to indicate heterogeneity of variance (as per Bartlett's test), a power transformation of the dependent variable was sought to stabilize the variance using the Box-Cox method (Box and Cox, 1964). The transformation that resulted in the minimum residual sum of squares, pooled over all studies for a given crop, was deemed the "best" transformation for the crop. The residual plots from the transformed data were inspected to determine if the normality and homogeneous variance assumptions had been adequately satisfied.

Dose-Response Models

Polynomial dose-response equations and Weibull dose-response equations were used to characterize yield responses to O_3. Both classes of response equations were developed to account for all effects in the data set being fit (e.g., block, cultivars, O_3, SO_2, moisture, and frustum top effects). Table 3 lists the seasonal O_3 and SO_2 dose metrics used for each study with the ranges of the plot mean values for these variables. Moisture and frustum top effects were considered qualitative factors. All main effects were retained in the final O_3 dose-response equations regardless of their significance. For presentation, the intercept was computed as the mean over blocks (if applicable). Since each equation accounted for all effects in the design, the residual mean square provided an estimate of experimental error. Covariates, suggested by the principal investigators, were used when they showed significance in the analysis of variance and the regression analyses. When data involving covariates were combined over studies, covariate values were centered to have mean zero within each study that contained covariate data. All values were set to zero in studies that did not contain the covariate.

All O_3 dose-response models were fitted using plot yield values on the original scale, kg ha^{-1} (gms $head^{-1}$ for barley), or on the transformed scale determined from the residuals analyses. The same scale was used for all studies within each crop. The weights, when weighted least squares was indicated by the residuals analyses, were determined from the error variances from the analyses of variance using the plot yield values on the appropriate scale. When the yield variable was transformed, the mean response function for the Weibull was similarly transformed. This maintains the interpretations of the Weibull parameters (Carroll and Ruppert, 1984).

When polynomial response models were being fit, the degree of the polynomial for the final O_3 dose-response equation was determined by testing the sequential sums of squares for the individual terms of a second or third degree polynomial and by a "lack-of-fit" test

(α=0.05) which compares the difference between the analysis of variance treatment sum of squares and the sum of squares accounted for by the polynomial with the analysis of variance mean square error. The lack-of-fit test is approximate because the sequential sums of squares for the polynomial equation, which uses the quantitative levels of O_3 for each plot, do not provide a valid partitioning of the treatment sum of squares since the replicate plots for a given treatment do not have identical levels of O_3. When responses were being tested for homogeneity over subsets of data, the degree of polynomial used for all subsets was determined by the highest degree polynomial needed to fit any one of the subsets.

Partial sums of squares were used when analyzing an unbalanced data set or studies that included a covariate. Partitioned treatment sums of squares were computed by adjusting the linear sums of squares for all other linear terms in the model, the quadratic sums of squares for all other quadratic terms and all linear terms, and so forth. All terms were adjusted for block effects and all covariates when applicable.

The basic Weibull response model (Rawlings and Cure, 1985) has the form

$$Y(x_i;\alpha,\omega,\lambda) = \alpha \exp\left[-\left(\frac{x_i}{\omega}\right)^{\lambda}\right] + \epsilon_i = \alpha\, H(x_i;\omega,\lambda) + \epsilon_i$$

where $Y(x_i;\alpha,\omega,\lambda)$ is yield (on the appropriate scale) and x_i is the seasonal O_3 mean in $\mu L\ L^{-1}$. The exponential part of the model, $H(x_i;\omega,\lambda)$, characterizes the proportional yield remaining at O_3 dose x_i. The parameter α allows for actual rather than proportional yield levels; α is the hypothetical yield at zero O_3 dose. The α parameter was extended as a linear function of effects to account for factors such as blocks, cultivars, SO_2, sites, and years. These additional effects in the extended α-term are referred to as the $\alpha(x)$ terms. In the NCLAN datasets, the effects of SO_2 were always adequately modeled by a linear term in the extended α-term. The parameter ω represents the O_3 dose at which the yield is reduced to 0.37α. The parameter λ is a dimensionless parameter controlling the shape of the O_3 response curve.

Convergence problems arose in a few cases when fitting the Weibull response model. When there was little or no response to O_3, the parameters of the Weibull response could not be defined from the data and convergence to a solution was not obtained. Consequently, the Weibull response model was not fit if both the analysis of variance and the polynomial response modeling indicated no significant effect of O_3.

Three categories of O_3 dose-response equations were computed. For studies involving more than one cultivar, O_3 dose-response equations were obtained for each cultivar and over subsets of cultivars showing homogeneous response to O_3. When moisture stress was a treatment factor, O_3 dose-response equations for each moisture stress level and combined over levels were computed and tested for homogeneity of response (α=0.05). *Within* each study, the yield response to O_3 was summarized with the smallest number of equations that the tests of homogeneity would permit; the resulting response curves are called Category I equations. Tests of homogeneity of response *among* studies were then used to group the responses into homogeneous subsets for each of which a response equation was computed; the equations for these homogeneous subsets are called Category II equations. The grouping of studies into subsets with homogeneous response to O_3 is dependent on the testing sequence and other groupings may be possible. Regardless of heterogeneity of response to O_3, all data were combined to develop one response equation for each crop. These "average" crop response equations are called the Category III equations.

Homogeneity of response over studies was tested using the difference in the residual sums of squares for "full" and "reduced" models (Rawlings, 1988, pp. 108-111). The "full" model allowed different yield responses to O_3 for subsets of the data; the "reduced" model imposed a common response to O_3 for all subsets. The residual mean square from the full model was used as the denominator in the F-test for each test of homogeneity for the Weibull response models. The appropriate analyses of variance estimates of error (pure error) were used as the denominator mean squares for the tests of homogeneity involving the polynomial response models. For the single-replicate studies, the estimate of error was obtained from the residual mean square from the polynomial model of one degree higher than indicated by sequential tests of significance (α=0.05).

The predicted values and residuals from the response equations were computed. Residual plots, normal plots, and plots of the predicted values superimposed on the data were used to evaluate the adequacy of the final O_3 dose-response equations.

Relative Yield Loss Estimation

Relative yield loss from O_3 was defined as the proportional decrease in mean yield that results from a change in the seasonal average level of O_3 from a reference level x_0 to some new level x_r, and is estimated as:

$$RYL = 1 - \frac{\hat{Y}_r}{\hat{Y}_0}$$

$$A(x) = (x/\hat{\omega})^{\hat{\lambda}} \ell n(x/\hat{\omega})$$

and

$$B(x) = (\hat{\lambda}/\hat{\omega})(x/\hat{\omega})^{\hat{\lambda}}.$$

Hence, the $100(1-\alpha)\%$ confidence interval estimate for relative yield loss using the linear approximation and normal theory is obtained as:

$$RYL \pm t(\alpha/2, \nu)\left[Var(RYL)\right]^{\frac{1}{2}}$$

where $t(\alpha/2, \nu)$ is the critical value of Student's t, with ν degrees of freedom, for a two-tailed test with significance level α.

Parameter estimates obtained from nonlinear regression are only asymptotically normal, even if the random errors are normally distributed, and variances of parameter estimates routinely provided are based on first-order linearizations of the nonlinear equations. Consequently, tests of significance, and confidence interval estimates as outlined above, that assume normality of the parameter estimates and use the estimated variances are approximations. Methods based on this approach are referred to as the Wald methodology (Gallant, 1987). The adequacy of the Wald methodology depends on the degree of curvature of the expectation surface, which is determined jointly by the model and the O_3 dose levels (Bates and Watts, 1988, pp. 36-39). The reader is referred to Dassel and Rawlings (1989) for discussion of the effect of choice of design points on degree of curvature for the Weibull response equation, and to Somerville, Dassel and Rawlings (1989) for comparisons of Wald confidence interval estimates with the more accurate, but computationally more demanding, likelihood ratio confidence interval estimates of RYL for representative NCLAN data sets.

The same basic methodology was followed in those cases where the Weibull equation was not fit and the polynomial response equations were used. In these cases, RYL was computed for each moisture level and/or SO_2 level (as appropriate) because the effects of moisture and SO_2 do not cancel in the RYL ratio for the polynomial as they do with the Weibull response model.

Analyses of variance were rerun using estimated weighted least squares for the seven crops that showed significant heterogeneity of variance. Residuals and normal plots using the residuals from the weighted analyses for alfalfa, cotton, kidney bean, and turnip (Figure 2) appeared random and normally distributed. Note that the residuals reported by PROC GLM (SAS Institute Inc., 1985) are unweighted residuals based on predicted values computed from the weighted analyses, and were reweighted before plotting. Although the residual and normal plots using the weighted residuals for corn, soybean, and wheat (Figure 3) were improved, they still showed indications of nonnormality and heterogeneity of variance.

The Box-Cox analysis applied to corn, soybean, and wheat indicated that the square-root transformation was necessary for all three crops. Bartlett's test applied to the transformed (but unweighted) data still indicated heterogeneity of variance in each case. The test statistics were smaller (less significant) on the transformed scale for corn and soybean, but larger (more significant) for wheat. Consequently, no transformation was used on the wheat data. The corn and soybean data were reanalyzed using estimated weighted least squares on the square root transformed data. The weighted residual and normal plots (Figure 4) showed only slight changes from the weighted and untransformed data. However, since the Box-Cox analysis (Box and Cox, 1964) had shown a significant (α=.05) reduction in the residual sums of squares from using the transformation, the square root transformation was used in subsequent analyses for corn and soybean.

Dose-Response Models

Based on the results from the residuals analyses, O_3 dose-response models were fitted using the original scale and ordinary least squares for barley, forage, lettuce, peanut, sorghum, tobacco, and tomato; using the original scale and weighted least squares for alfalfa, cotton, kidney bean, turnip, and wheat; and using the square root transformation and weighted least squares for corn and soybean.

The Category I polynomial O_3 dose-response equations are given in Table 4. The polynomial modeling showed significant heterogeneity of response to O_3 as follows:

(1) Among cultivars of corn in the Argonne 1985 study, of turnip in the Raleigh 1980 study, and of wheat in the Argonne 1982 study.

(2) Among moisture stress levels for cotton in the California 1981 and Raleigh 1985 studies, and for soybeans in the Argonne 1986, Beltsville 1983, and Raleigh 1986 studies.

(3) Among levels of SO_2 in the Raleigh 1982 cotton study.

This $SO_2 \times O_3$ interaction was reported as nonsignificant by Heagle et al. (1986, 1988) based

on a different analysis. The analyses reported by Heagle included ambient air plots and used 7 h treatment mean levels of O_3. The changes in the analyses caused the p-levels for the test of significance of the $SO_2 \times O_3$ interaction to change from .09 in his analysis to .01 in this analysis.

The Category I Weibull O_3 dose-response equations are given in Table 5. Note that no Weibull equation is shown for Argonne 1984 alfalfa, California 1982 and 1983 barley, and California 1985 cotton. These studies showed no significant effect of O_3 on yield and, consequently, the Weibull model was not fit. The Weibull modeling showed significant heterogeneity of yield response to O_3 as follows:

(1) Among cultivars of corn in the Argonne 1985 study, and of wheat in the Argonne 1982 study.

(2) Among moisture stress levels for cotton in the California 1981 and Raleigh 1985 studies and for soybean in the Argonne 1986, Beltsville 1982, and Beltsville 1983 studies.

Unlike the polynomial models, the Weibull models showed no significant heterogeneity in yield response to O_3 caused by different exposure levels of SO_2. It should be noted that O_3 is modeled in the Weibull model as a multiplicative effect, rather than as additive effects as in the polynomial models. Consequently, homogeneity of response has different meanings for the two models.

The Category II O_3 dose-response equations are shown in Table 6 for the polynomial model and in Table 7 for the Weibull model. These equations combined information from different studies within the same crop for which the responses to O_3 could be considered homogeneous. In all cases, subsets of data within a study that showed significant heterogeneity were kept separate throughout the testing for Category II equations. Effects were included in the model to allow each study-cultivar-block combination to have unique yield levels. These estimates (averaged over blocks for each study-cultivar combination) are listed under the "intercept" heading in Table 6 and under the "α" heading in Table 7. The linear effects of moisture (M), sulfur dioxide (S), covariates (cov), and the presence of a frusta top on the chamber (T) are listed as the $\hat{\alpha}(x)$ terms. The estimates of the parameters of the Weibull response function are listed under the headings $\hat{\omega}$ and $\hat{\lambda}$. Standard errors for the Weibull parameter estimates were computed from the first-order approximations of the variances as provided by the nonlinear least squares program.

The fitted Category II response equations and the corresponding data are shown in Figures 5-14. If data from a study or a portion of a study were not included in a Category II equation (i.e., because of heterogeneous response to O_3) then the Category I response equation

and corresponding data are shown in these figures. Tables 4-7 list the parameter estimates for the Category I and II equations and include references to the appropriate figure. The regression line in each figure expresses yield relative to that at O_3 = .025 μL L^{-1}. For plotting purposes, the data points have been adjusted to remove all effects except the relative O_3 effects and random error; that is, site, year, cultivar, linear SO_2, and linear moisture effects have been removed. This adjustment was dependent on the type of model used. Hence, there may be small differences in the values of a given adjusted data point between the polynomial and Weibull plots.

The Category III response equations are summarized in Table 8 for the polynomial and in Table 9 for the Weibull. The format for reporting the Category III equations is the same as that for the Category II equations. Each equation includes α-terms for all site, year, block, cultivar, and linear moisture, SO_2, covariate, and frustum to effects. The Category III response curve is the best fitting common response curve for all data for each crop. All Category III equations for crops studied over more than one environment combined data that exhibited heterogeneous response to O_3 except:

a) the tomato polynomial and Weibull equations, and

b) the barley polynomial equation. (No Weibull equation was fit to the barley data.

The Category III equations represent an "average" response to O_3 for each crop based on all NCLAN data, but they should be regarded as approximations and used with caution. Neither the sampling of cultivars nor the sampling of environmental conditions by the NCLAN studies can be considered to adequately represent the commercial production of the crop.

Covariates were significant and remained in the model for five studies (% virus infected plants for Argonne 1980 soybean, and Argonne 1982 and 1983 wheat; total fresh fruit weight in companion plots for 1981 tomato; and relative plant density for Ithaca 1984 forage). A covariate for the tobacco study (a measure of total leaf area before exposures were started) was nearly significant (α=0.05) in the analysis of variance but was not significant in the O_3 dose-response equations. The polynomial and Weibull parameter estimates with the covariate in the equations are given in Heagle et al. 1987.

The relative merits of the polynomial versus the Weibull can be judged from inspection of Figures 5-14 and comparisons of the residual sums of squares shown in Tables 10-12. It is important to remember that the number of degrees of freedom should be considered when making these comparisons. Also, since the combining of data into Category II responses depended on the tests of significance for the specific equations, not all Category II residual sums of squares are comparable. Of the 55 sets of equations that may be compared, the

polynomial residual sum of squares was greater than the Weibull residual sum of squares in 28 cases.

Relative Yield Losses

The 95% confidence interval estimates (Wald approximations) of relative yield losses were computed using the homogeneous Category II Weibull O_3 dose-response equations (Table 13). The relative losses are expressed in terms of percentage yield loss corresponding to a change in seasonal O_3 mean from .025 μL L^{-1} to a given (higher) seasonal mean level. The relative yield loss for data not included in a Category II equation was based on the appropriate Category I equation. Relative yield loss for barley was computed using the polynomial Category II equation since no Weibull equations were computed for these data. The intervals of primary interest are those for O_3 = .04 μL L^{-1} to .06 μL L^{-1}, which represent the estimated penalty being paid for current levels of O_3 pollution, or the benefits that might be realized with more restrictive standards on O_3.

DISCUSSION

The yield responses to O_3 were modeled using both the polynomial response model and the nonlinear Weibull response model. The polynomial model was used because it is generally familiar to researchers. However, polynomial models do not represent plateau-type responses well. It is difficult to compare polynomial equations of different degrees, and the parameters cannot in general be considered biologically realistic. The Weibull model was used because its decreasing sigmoidal form was thought to be biologically more realistic and it "covered" the types of responses being observed in the NCLAN studies. Furthermore, the parameters of the Weibull model have a direct, meaningful interpretation. The form of the Weibull model, a monotonically decreasing function, would invalidate its use as a model, at least without modification, if it were believed that increased levels of O_3 could be beneficial. Perhaps plants adapted to current levels of O_3 would actually perform less well at lower levels of O_3. While there were cases in which the observed yields at ambient levels of O_3 were greater than those from the charcoal filtered treatments, the majority of the time this was not the case. Considering all NCLAN data as a whole, there was no statistical support for the hypothesis of increased yields associated with the increase in O_3 from the charcoal filtered treatments to the ambient air treatments (Rawlings, Lesser, and Dassel, 1988).

In general, the polynomial and Weibull models provided very similar degrees of fit to the data as reflected in the residual sums of squares. In some cases the differences in residual sums of squares were nontrivial, even after accounting for differences in numbers of degrees of freedom. The major differences arose in the following circumstances:

(1) Curvature of response was present but was not sufficient to cause terms of higher degree than the linear to be included in the polynomial equation. Consequently, the Weibull model, which accounts for the curvature, provided a smaller residual sum of squares than the linear polynomial model. This is illustrated with the peanut, the Beltsville 1983 soybean, *Shogoin* and *Purple Top White Globe* turnip data, and the Argonne 1982 Roland wheat Category I equations. In these cases, a higher degree polynomial model would have produced residual sums of squares similar to those of the Weibull.

(2) Plateau-type responses at low O_3 levels sometimes were not well represented by a quadratic polynomial response equation. The quadratic equation would tend to under estimate yield at the charcoal filtered O_3 level and over estimate yield at O_3 dose levels near ambient. This results in an overestimate of yield losses for higher levels of O_3. The Weibull model provided the better fit in these cases. This is illustrated by the 1982 kidney bean data (Figure 9.c and 9.d).

(3) Presence of a significant interaction for the polynomial model but not for the Weibull model between O_3 and another treatment factor led to polynomial response equations that allowed for different responses to O_3 for the levels of the other treatment factor whereas a common response was used for the Weibull. In such cases, the residual sum of squares for the Weibull was larger. This occurred in the Raleigh 1982 cotton data where the $O_3 \times SO_2$ interaction was significant, and in the Argonne 1986 and Raleigh 1986 soybean data where the $O_3 \times$ moisture stress interaction was significant in the polynomial equations.

The above differences in Category I equations can carry over into the Category II and III equations involving the same data causing differences in residual sums of squares. Inspection of the response curves with the data superimposed provided no indication of any systematic lack of fit for the Weibull response model.

In some individual studies (Argonne 1984 alfalfa, California 1982 and 1983 barley, and California 1985 cotton), the yield response to O_3 was not sufficient to provide adequate definition of the Weibull reponse curve, and consequently convergence to a solution in the nonlinear program was not obtained. The model in such cases is more complex than is warranted by the response shown in the data. If convergence is obtained when there is only marginal response, the parameters are not well defined and the variances of their estimates tend to be large. This high degree of uncertainty concerning the shape of the O_3 dose-reponse curve was exhibited by some of the Category I equations; for example, $\hat{\lambda} = 70.7 \pm 156$ for Argonne 1986 soybean, M=0, or $\lambda = 10.1 \pm 12.6$ for Argonne 1985 soybean. The magnitude of the standard errors indicate instability in these estimates. In addition, the $\hat{\lambda}$'s are unrealistically large. As λ increases, yield loss becomes increasingly concentrated around $O_3 = \omega$. For $\lambda = 10.1$, yield has decreased by only 5% at $O_3 = .75\omega$ but by 95% at $O_3 = 1.11\omega$; for $\lambda = 70.7$, the corresponding O_3 dose levels for the same change in yield are $O_3 = .93\omega$ and 1.02ω. In effect, nearly any value of λ would suffice for these cases because the observed yield responses were not sufficient to define the shape of the curves.

Dassel and Rawlings (1988) emphasize the importance of placement of the highest O_3 dose level for efficient estimation of the Weibull parameters. Dassel (personal communication) has also demonstrated that, when the maximum O_3 dose level is so low that the shape of the response curve has not been well defined, the first-order approximations of the variances are likely to be seriously inadequate, as shown by Clarke's (1987) measures of parameter-effects curvature. These are general problems that apply to any nonlinear model; the data must adequately display the major features of the response equation for the estimates and the first-order approximations of the variances to be well behaved. More exact approximations of the

variances and simulations for special cases have shown that the first-order approximations of the variances for the Weibull model tend to seriously overestimate the true variances when there is a breakdown in the first-order approximations (Dassel, 1987).

Such extreme difficulties occurred only occasionally in the NCLAN studies. While the maximum O_3 dose level was never in the optimum range (peanuts came close with the maximum O_3 dose at $1.15\hat{\omega}$) for estimation of parameters (Dassel and Rawlings, 1988), sufficient response to O_3 was obtained for most of the studies to provide convergence and reasonable estimates of the parameters. In the cases where information was combined from more than one study, the estimates were reasonably precise; the standard errors on $\hat{\omega}$ varied from 2% to 33% and the standard errors on $\hat{\lambda}$ varied from 9% to 47% of their respective estimates.

These estimates probably would not be considered sufficiently precise if primary interest were in the parameters per se. However, primary interest in these analyses is in the use of the fitted regression lines for estimation of relative yield losses, and points on the regression line may be estimated with reasonable precision even though the individual parameters may not be. Consequently, a better judgement of the precision of the results for the purpose of the NCLAN studies is provided by the confidence interval estimates of the relative yield losses.

The confidence interval estimates of relative yield loss are based on the Wald approximation. The first-order approximations of the variances provided by the nonlinear regression program are used and the estimates are assumed to be normally distributed. In addition, the variances of the relative yield ratios are approximated using a first-order Taylor's series expansion of the ratio. It is known that the approximate confidence limits on the parameters obtained with the Wald approximation can be inadequate in some cases (Gallant, 1987). Consequently, the confidence limits on the relative losses should be used only as guides. Comparisons of the Wald confidence limits with more exact confidence interval estimates using the likelihood ratio statistic (Gallant, 1987) and the Clarke adjustment (Clarke, 1987) have been made for several NCLAN studies by Somerville, Dassel, and Rawlings (1989). Results indicate generally good agreement between the Wald relative yield loss confidence intervals and the likelihood ratio confidence intervals for individual studies that exhibited low variability and that included a sufficient range of O_3 to characterize the response curve, and for all of the combined studies investigated (which contained between 59 and 208 observations each).

All crops that had received more than minimal testing showed heterogeneous response to O_3. Heterogeneity of response to O_3 over different cultivars in the same study (corn,

soybean, and wheat) suggests the presence of genetic variability for sensitivity to O_3. The heterogeneity of observed responses over studies could be due to genetic differences in the cultivars being used, or to any of many soil, climatological, and management differences. In these analyses, the pooled effects of all such differences were absorbed in fixed effects assigned to each study. The standard errors of the estimates were computed using this fixed effects model and, consequently, the standard errors are undoubtedly too small for general inferences of the effects of O_3. Proper estimates of precision for regional and national inferences would require that the inconsistencies of response over a proper sample of environments be taken into account. While the sampling of environments for such studies can never be truly random, more reasonable estimates of precision would be obtained by regarding the environments encountered in the NCLAN studies as random. This approach was not used because no computing program was available at the time that these analyses were done that accomodated nonlinear models with variance components.

The "average" species response equations (Category III) showed that O_3 had a significant negative impact on crop yields of 13 of the 14 crops tested in the NCLAN program. The estimated relative yield losses for a change in O_3 from .025 to .05 μL L^{-1} (7 h or 12 h metric according to crop) varied from less than 1% (barley, lettuce) to as much as 20% (soybean). The nature of the response varied from a nearly linear response for kidney bean, soybean, tobacco, and tomato (λ=1.35 to 1.67), to a slightly delayed response (plateau at low O_3 levels) for alfalfa, cotton, forage, peanut, and sorghum (λ=1.95 to 2.27), to the more marked delay in response of corn, lettuce, turnip, and wheat (λ=2.56 to 9.76). Moisture stress also had a negative impact on crop yield for all species in which moisture effects were studied. In five studies there was significant heterogeneity between the O_3 response curves for the different moisture stress levels, and in four of the five cases the effect of the stress was to reduce the negative effect of O_3. The additional pollutant SO_2 caused a significant decline in yield in some individual studies but in only one case was there an indication of a significant effect of SO_2 on the O_3 response curve.

It should be recognized that the "average" O_3 response curve for each crop for a variety of reasons is not a valid characterization of the average effect of O_3 pollution on agricultural production for the crop. The environments sampled for even the most studied crop, soybeans, cannot be considered an adequate and representative sample of the environments for soybean production. While efforts were made to use the commercially important cultivars, only a few cultivars were used for each crop, and the "averaging" of the responses over cultivars did not take into account the relative economic importance of the cultivars. Similarly, one could argue that information from different test sites should be

weighted according to economic importance of the region to the overall agricultural production for the species. Because of the observed heterogeneity of responses to O_3 over cultivars, moisture stress levels, and test environments, the "average" species response curve will depend on the weighting used in combining the data. We have weighted each observation equally in these analyses (versus, for example, weighting each site equally). In spite of these inadequacies, the Category III O_3 dose-response equations provide a useful summary of the NCLAN information on the response of the crop to O_3. While there may be bias in the results due to the inadequate sampling and method of averaging already mentioned, the inadequacy of the measures of precision is of more immediate concern. The fixed model approach has undoubtedly provided overly optimistic measures of precision. More realistic impressions of the variability in yield response to O_3 can be gained from inspection of the range of responses in the homogeneous Category II equations.

The NCLAN program was the most extensive coordinated project to investigate the effects of air pollution on major agricultural species. The approach of using controlled experimentation has clearly demonstrated important detrimental causal effects of O_3 pollution on 13 of 14 crops studied, and has quantified the relationship in O_3 dose-response equations. The research has demonstrated that sensitivity to O_3 damage can be influenced by the degree of moisture stress under which the plants are grown, but only one study (out of 12) gave evidence that presence of SO_2 pollution has an effect on the nature of the O_3 response curve. There undoubtedly are other environmental factors yet to be identified that alter the impact of O_3, as suggested by the heterogeneity of response among studies. More research is needed to identify other important interacting factors, to study the mechanisms of O_3 pollution damage, and to more adequately characterize the O_3 dose-response relationships.

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APPENDIX A

ABSTRACTS

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APPENDIX B

Method for Estimating Missing Hourly Ozone Readings

Each hour of the exposure period (e.g., 900 to 1600 h s of each day during the dispensing season) is checked for missing O_3 data. The method employed for estimating missing data depends on the available data. For any hour in which all values are missing for all treatments, it is assumed that dispensing of O_3 was not taking place in which case reasonable estimates of ambient levels of O_3 (as described below) are used for all NF and NF+ treatments. The protocol for substituting missing values is as follows:

1. Replicate data for the treatment are available:
   Whenever some of the replicate data for a particular treatment are available for a given hour, the mean (rounded) of the available replicate(s) for each hour is substituted for the missing replicate(s) for that hour.

Example 1

Before:

CF_1	CF_2	CF_3	NF_1	NF_2	NF_3	CA30_1	CA30_2	CA30_3
.013	.016	.	.035	.	.038	.	.	.092

After:

CF_1	CF_2	CF_3	NF_1	NF_2	NF_3	CA30_1	CA30_2	CA30_3
.013	.016	.015	.035	.037	.038	.092	.092	.092

The missing value at CF_3 is replaced by the mean of CF_1 and CF_2. Likewise, the missing value at NF_2 is replaced by the mean of NF_1 and NF_3. The values for CA30_1 and CA30_2 are from CA30_3.

2. Replicate data are available for NF but not available for CF and NF+:
   When no replicate data are available for the CF and NF+ treatments for a given hour, the mean of the available NF replicates for the hour is:
   a) substituted directly for the hourly O_3 values for all NF+ treatments, and
   b) multiplied by the ratio of the seasonal CF mean to the seasonal NF

mean (obtained from annual reports) for the hourly O_3 value for the CF treatment.

Example 2

seasonal means: CF=.014

NF=.039

ratio CF/NF = .359

Before:

CF_1	CF_2	CF_3	NF_1	NF_2	NF_3	CA30_1	CA30_2	CA30_3
.	.	.	.035	.	.038	.	.	.

After:

CF_1	CF_2	CF_3	NF_1	NF_2	NF_3	CA30_1	CA30_2	CA30_3
.013	.013	.013	.035	.037	.038	.037	.037	.037

The mean of the values for NF_1 and NF_3 are used to replace the missing values for NF_2, CA30_1, CA30_2, and CA30_3. This mean is multiplied by the CF/NF ratio and substituted for the missing values for CF_1, CF_2, and CF_3.

3. All values for all treatments are missing for the given hour:

When all O_3 values are missing for a given hour,

a) the seasonal mean for CF is substituted for the missing hourly readings for the CF treatment, and

b) the seasonal mean for NF is substituted for the missing hourly readings for the NF and NF+ treatments. In the event that ambient air (AA) was monitored during the hour, the seasonal NF mean is adjusted by multiplication by the ratio of the seasonal mean for NF to the seasonal mean for AA.

Example 3

seasonal means: CF=.014
NF=.039
AA=.045
ratio CF/NF=.359
ratio NF/AA=.867

Before:

CF_1	CF_2	CF_3	NF_1	NF_2	NF_3	CA30_1	CA30_2	CA30_3
.	.	.	.	.	.	.	.	.

After:

a) If AA was not monitored on non-dispensed days then the seasonal mean for CF is used to replace the missing values for CF and the seasonal mean for NF is used to replace the missing values for the NF and NF+ treatments. This results in the following:

CF_1	CF_2	CF_3	NF_1	NF_2	NF_3	CA30_1	CA30_2	CA30_3
.014	.014	.014	.039	.039	.039	.039	.039	.039

b) If AA was monitored on non-dispensed days (e.g. AA=.043 for this particular hour) then the missing values for CF are replaced by the value for AA multiplied by the ratio of the CF seasonal mean to the AA seasonal mean. The missing values for NF and NF+ treatments are replaced by the value for AA multiplied by the ratio of the NF seasonal mean to the AA seasonal mean. This results in the following:

CF_1	CF_2	CF_3	NF_1	NF_2	NF_3	CA30_1	CA30_2	CA30_3
.013	.013	.013	.037	.037	.037	.037	.037	.037

APPENDIX C

Conversion of 7 h ozone means to 12 h means

Whenever analyses are to be combined over studies in which at least one study has a 12 h exposure period, all dose metrics are to be standardized to a 12 h metric. The standardization will use estimates of ambient levels of O_3 when O_3 dispensing was not taking place. The following procedures will be used to ensure consistency:

1. When the 24 h ambient air O_3 data set is available:

   a) If CF, HF, and NF are available in the 24 h data set, then the additional 5 h needed to create a 12 h period will be taken from this data set. The CF or HF 12 h period will be completed with the 5 h CF or HF values, respectively. All other treatments will be completed with the 5 h NF values.

$$12\text{ h mean} = \frac{\{\ 7(7\text{ h mean}) + 5(5\text{ h mean})\ \}}{12}$$

   b) If only AA is available in the 24 h data set, then the ratio of the 7 h NF to 7 h AA will be computed and multiplied by the 5 h AA to create a 5 h NF. A similar ratio will be computed for a 5 h CF. These created 5 h values will be added to the 7 h values as mentioned in part a, above.

$$12\text{ h mean} = \frac{\{\ 7(7\text{ h mean}) + 5(X/AA7\text{ h})(AA5\text{ h mean})\ \}}{12}$$

   where X = 7 h CF, 7 h HF, or 7 h NF.

2. When the 24 h O_3 data set is not available:

   If there are no 24 h data that correspond with the O_3 dispensing period, then it must be assumed that the ratio between CF and NF are consistent from year to year for a given site and time period. For example, if the ratio between CF and NF at Riverside is .36 in 1981, based on the 7 h seasonal means, it is assumed that the ratio between CF and NF at Riverside in 1985 based on the 7 h seasonal means will also be approximately .36. This does not assume that the NF values will be equal from one year to the next for a given site and time period. Therefore, a relationship between the two years must also be established. With these assumptions, the additional 5 h values needed to compute a 12 h mean, can be computed by calculating a series of ratios between the two years.

a) If year "A" has 7 h dispensing and no 24 h data set, and year "B" has 12 h dispensing, then the ratio between the 7 h NF in year "A" and the 7 h NF in year "B" will be multiplied by the additional 5 h NF in year "B" to create a 5 h NF for year "A". From this a 5 h CF or HF for year "A" can be computed and the values used as explained in parts 1.a and 1.b.

b) If year "B" has only 7 h dispensing but also has a 24 h data set, then the additional 5 h values will be computed from the 24 h data set, as in part 1.a or 1.b, and multiplied by the ratio of the 7 h NF from "A" to the 7 h NF from "B" as mentioned in part 2.a.

Two conditions should be met in order for these "across years" additions to be made:

1. Both years of data must have been collected from the same site (e.g., both years from Riverside, CA).
2. Both years of data should be close to the same seasonal time frame (e.g., year "A" was from June 12 to October 10, 1981; year "B" was from June 2 to September 30, 1985). It is not necessary that both years were exposing the same crop.

$$12\text{ h mean}A = \frac{\{\ 7(7\text{ h mean}A) + 5(x)(z)(5\text{ h mean}B)\ \}}{12}$$

where x = the ratio of 7 h CF or HF from year "A" to the 7 h NF from year "A". If calculating means other than CF or HF then x=1 since 7 h NF/7 h NF = 1.

z = the ratio of 7 h NF from year "A" to the 7 h NF from year "B".

Table 1. Abbreviations used in tables and figures.

I. Study:

First letter denotes site:

A = Argonne, Il
B = Beltsville, Md
C = California
I = Ithaca, NY
R = Raleigh, NC

The two numbers following the letter denote year:

80 = 1980, 81=1981, etc.

Example: A80 = Argonne 1980

II. Model variables:

O = ozone dose metric
S = sulfur dioxide dose metric
COV = covariate
M = moisture indicator variable:
M=0 for water-stressed treatment
M=1 for well-watered treatment
M=0.4622 for intermediate moisture treatment (used only for C85 cotton*)
T = top indicator variable:
T=1 for frustum top present
T=0 for no frustum top

See Table 3 for more detail concerning the exact definition of and data ranges for variables by study.

III. Others:

OLS = ordinary least squares
WLS = weighted least squares
N/A = not applicable

* The value of M=0.4622 was computed using linear interpolation of the yield means for each of the three moisture levels in the C85 cotton study.

Table 2. Summary of experiments in the NCLAN program

Crop (Species) Study code[1]	Site[2]	Year	Cultivar(s)	Levels of Ozone	Number of Chambers[3]	Levels of other Treatments
ALFALFA (*Medicago sativa* L.):						
C84	Shafter	1984	WL-514	6	24	2 moisture
C85	Shafter	1985	(Second year growth of C84)			
A84	Argonne	1984	WL-312	6	40	4 SO_2
BARLEY (*Hordeum vulgare* L.):						
C82	Riverside	1982	Poco	7	24	
C83	Riverside	1983	CM-72	7	24	2 moisture
CORN (*Zea mays* L.):						
A81	Argonne	1981	Pioneer-3780, PAG-397	7	20	
A85	Argonne	1985	Pioneer-3780, FR20A × FR634, FR20A × FR35, LH74 × FR23,	8	42	3 SO_2
COTTON (*Gossypium hirsutum* L.):						
C81	Shafter	1981	Acala SJ2	7	24	2 moisture
C82	Shafter	1982	Acala SJ2	7	24	2 moisture
C85	Shafter	1985	Acala SJ2	5	24	3 moisture
R82	Raleigh	1982	Stoneville 213	6	25	4 SO_2, frusta top
R85	Raleigh	1985	McNair-235	6	20	2 moisture
FORAGE						
a. red clover/timothy mixture (*Trifolium pratense* L./*Phleum pratense* L.):						
I84	Ithaca	1984	Arlington/Chaplain	5	32	4 SO_2
I85	Ithaca	1985	Arlington/Chaplain	5	32	4 SO_2
b. ladino clover/tall fescue (*Trifolium repens* L./*Festuca arundinacea* Schreb.):						
R84	Raleigh	1984	Regal/Kentucky 31	7	24	2 moisture
R85	Raleigh	1985	(Second year growth of R84)			
KIDNEY BEAN (*Phaseolus vulgaris*):						
I80	Ithaca	1980	CA Light Red	6	20(15)	
I82	Ithaca	1982	CA Light Red	6	20	
LETTUCE (*Lactuca sativa* L.):						
C83	Riverside	1983	Empire	7	24	
PEANUT (*Arachis hypogaea* L):						
R80	Raleigh	1980	NC-6	6	20	
SORGHUM (*Sorghum vulgare* Pers.):						
A82	Argonne	1982	DeKalb A28+	7	20	
SOYBEAN (*Glycine max* L. Merr.):						
A80	Argonne	1980	Corsoy	6	20	
A83SO2	Argonne	1983	Amsoy, Corsoy	5	16	4 SO_2

Table 2. (continued)

Crop (Species) Study code[1]	Site[2]	Year	Cultivar(s)	Levels of Ozone	Number of Chambers[3]	Levels of other Treatments
SOYBEAN (continued)						
A83cv	Argonne	1983	Amsoy, Corsoy, Pella, Williams	5	24	
A85	Argonne	1985	Corsoy	6	20	2 moisture
A86	Argonne	1986	Corsoy	6	30	2 moisture
B81	Beltsville	1981	Williams, Essex	4	30	6 SO_2
B82	Beltsville	1982	Williams, Forrest	5	30	3 SO_2 2 moisture
B83	Beltsville	1983	Williams, Corsoy	6	30	2 moisture
I81	Ithaca	1981	Hodgson	6	20	
R81	Raleigh	1981	Davis	7	48	4 SO_2
R82	Raleigh	1982	Davis	9	16	
R83	Raleigh	1983	Davis	5	24(23)	2 moisture
R84	Raleigh	1984	Davis	7	24(23)	2 moisture
R86	Raleigh	1986	Young	6	30	3 moisture
TOBACCO (*Nicotiana tabacum* L.):						
R83	Raleigh	1983	McNair-944	12	22	
TOMATO (*Lycopersicon esculentum* Mill.):						
C81	Livermore	1981	Murietta	5	32(29)	6 SO_2
C82	Livermore	1982	Murietta	5	32(30)	6 SO_2
TURNIP (*Brassica rapa* L.):						
R80	Raleigh	1980	Just Right, Shogoin, Tokyo Cross, Purple Top White Globe	6	20	
WHEAT (*Triticum aestivum* L.):						
A82	Argonne	1982	Abe, Arthur, Roland	6	20	
A83	Argonne	1983	Abe, Arthur	6	24(12)	
I82	Ithaca	1982	Vona	6	20	
I83	Ithaca	1983	Vona	5	40	4 SO_2

[1] Study code: Site (A=Argonne, B=Beltsville, C= California, I=Ithaca, R=Raleigh) followed by year.

[2] Site locations: Argonne=Argonne National Laboratory, Illinois, L. W. Kress and J. E. Miller, Principal Investigators; Beltsville=Beltsville Agricultural Research Station Beltsville, Maryland, H. E. Heggestad, Principal Investigator; Ithaca=Boyce Thompson Institute, Cornell University, New York, R. J. Kohut, Principal Investigator; Livermore=Laurence Livermore National Laboratory, Livermore, California, G. Bingham, Principal Investigator; Raleigh=N. C. State University, Raleigh, North Carolina, A. S. Heagle, Principal Investigator; Riverside=Riverside Air Pollution Laboratory, Riverside, California, P. J. Temple and O. C. Taylor, Principal Investigators; Shafter=Shafter Research Station, Shafter, California, Patrick Temple and O. C. Taylor, Principal Investigators.

[3] Number in parentheses is number of chambered plots used in analyses. Remainder dropped as per instructions from principal investigators.

Table 3. Definition and ranges of pollutant exposure metrics used as independent variables in the response equations.

Crop	Study	Ozone metric[1] Range	h day^{-1}	Sulfur dioxide metric[2] Range	h day^{-1}
ALFALFA	A84	.015–.084	12 h	.0–13.6	sum[3]
	C84	.015–.110	"	n/a	
	C85	.009–.096	"	n/a	
BARLEY	C82	.019–.071	7 h	n/a	
	C83	.014–.063	"	n/a	
CORN	A81[4]	.012–.108	12 h	n/a	
	A85	.014–.129	"	.007–.122	4 h
COTTON	C81[4]	.018–.109	12 h	n/a	
	C82[4]	.012–.087	"	n/a	
	C85	.015–.081	"	n/a	
	R82[4]	.022–.081	"	.0–.363	4 h
	R85	.020–.076	"	n/a	
FORAGE	I84	.017–.067	12 h	.004–.016	24 h
	I85	.018–.065	"	.004–.035	"
	R84	.025–.088	"	n/a	
	R85	.029–.092	"	n/a	
KIDNEY BEAN	I80	.024–.164	7 h	n/a	
	I82	.017–.113	"	n/a	
LETTUCE	C83	.020–.129	7 h	n/a	
PEANUT	R80	.025–.125	7 h	n/a	
SORGHUM	A80	.015–.129	7 h	n/a	
SOYBEAN	A80[4]	.017–.080	12 h	n/a	
	A83SO2[4]	.019–.068	"	.02–.56	4 h
	A83cv[4]	.013–.070	"	n/a	
	A85[4]	.014–.080	"	n/a	
	A86[4]	.010–.096	"	n/a	
	B81[4]	.012–.050	"	.003–.237	4 h
	B82[4]	.012–.069	"	.002–.072	4 h
	B83[4]	.014–.090	"	n/a	
	I81[4]	.015–.070	"	n/a	
	R81[4]	.019–.087	"	0–.395	4 h
	R82[4]	.016–.081	"	n/a	
	R83[4]	.026–.076	"	n/a	
	R84[4]	.020–.075	"	n/a	
	R86	.015–.088	"	n/a	
TOBACCO	R83[4]	.026–.115	12 h	n/a	

Table 3. (continued)

Crop	Study	Ozone metric[1] Range	h day^{-1}	Sulfur dioxide metric[2] Range	h day^{-1}
TOMATO	C81	.008–.105	7 h	.001–.242	7 h
	C82	.008–.054	"	.0–.234	"
TURNIP	R80	.014–.096	7 h	n/a	
WHEAT	A82	.023–.124	7 h	n/a	
	I83	.017–.096	"	n/a	
	I82	.020–.106	"	n/a	
	I83	.023–.104	"	.0–0.362	4 h

[1] all ozone metrics are seasonal exposure means for the specified number of hours per day expressed in μL L^{-1}.

[2] all sulfur dioxide metrics are seasonal exposure means for the specified number of hours per day expressed in μL L^{-1} except A84 alfalfa.

[3] Seasonal exposure sum expressed in μL h L^{-1}. The total number of exposure hours ranged from zero (for zero sulfur dioxide treatment) to 96 (for highest sulfur dioxide treatment).

[4] These studies dispensed ozone for 7 h per day, but analyses were based on 12 h means computed according to the protocol in Appendix C.

Table 4. Parameter estimates for the Category I polynomial equations. Standard errors of estimates are given in parentheses[a]. Figure references are in brackets for those equations represented in Figures 5-14.

Crop Studies in model:	Intercept(s)	O	O^2	O^3	Other[b]	
ALFALFA						
1. A84 [5.c]	1418	509	–	–	S:	−36
		(1361)				(24)
					S^2:	3.0
						(1.7)
2. C84	27559	−98129	–	–	M:	3380
		(10314)				(696)
3. C85	20464	−40293	–	–	M:	10897
		(17823)				(1496)
					OxM:	−62439
						(25058)
BARLEY (yield is grams per head)						
1. C82	2.00	−0.686	–	–	–	
		(1.864)				
2. C83	1.80	−2.267	–	–	M:	0.358
		(2.495)				(0.079)
CORN[c]						
1. A81 [6.a]						
Pioneer	97	511	−7672		–	
PAG-397	105	(90)	(728)			
2. A85 Pioneer and LH74xFR23 [6.c]						
Pioneer	103	198	−3413	–	S:	4
LH74xFR23	106	(93)	(628)			(17)
3. A85 FR20AxFR35 and FR20AxFR634 [6.e]						
FR20AxFR35	109	217	−4694	–	S:	−14
FR20AxFR634	118	(102)	(689)			(18)
COTTON						
1. C81 (M=1)	13898	25077	−942524	–	–	
		(31221)	(247236)			
2. C81 (M=0)	6437	107781	−1095825	–	–	
		(58256)	(453353)			
3. C82	5008	20356	−679910	–	M:	201
		(4591)	(245334)			(268)
4. C85	5947	−2242	–	–	M:	4877
		(19721)				(1127)

Table 4. (continued).

Crop Studies in model:	Intercept(s)	O	O^2	O^3	Other[b]	
COTTON (continued)						
5. R82	3186	24997 (10771)	−622548 (111987)	–	S: T: OxS:	−2003 (944) 46 (100) 43646 (15984)
6. R85 (M=0) [7.e]	3698	−10963 (5449)	–	–	–	
7. R85 (M=1)	4976	−36305 (9574)	–	–	–	
FORAGE						
First Year Studies:						
1. I84 [8.a]	4847	−31803 (7348)	–	–	S: Cov:	−15662 (28435) 3921 (1012)
2. I85 [8.b]	1962	−4873 (5680)	–	–	S:	−7811 (7243)
3. R84	11270	−43925 (4766)	–		M:	1142 (203)
Second Year Study:						
R85	9474	−52346 (8105)	–	–	M:	897 (332)
Combined Year Study:						
R84 & R85	20683	−96017 (10949)	–	–	M:	2067 (456)
KIDNEY BEAN						
1. I80 [9.a]	2799	1468 (3801)	−42317 (20686)	–	–	
2. I82 [9.c]	2456	2049 (8310)	−139749 (61787)	–	–	
LETTUCE						
C83 [10.a]	29730	1286071 (375083)	−11141631 (2486001)	–	–	
PEANUT						
R80 [10.c]	8718	−53462 (2570)	–	–	–	

Table 4. (continued).

Crop Studies in model:	Intercept(s)	O	O^2	O^3	Other[b]	
SORGHUM						
A80 [10.e]	8448	−10550 (2564)	–	–	–	
SOYBEAN[c]						
1. A80	51	106 (125)	−3809 (1224)	–	Cov:	−1.7 (0.8)
2. A83SO2						
Amsoy	42	272	−5044	–	S:	−12.2
Corsoy	38	(187)	(2128)			(2.6)
3. A83cv (WLS)						
Amsoy	48	−170	–	–	–	
Corsoy	48	(28)				
Pella	55					
Williams	52					
4. A85	53	−51 (35)	–	–	M:	7.7 (1.5)
5. A86	67	−649	16661	−115757	M:	15.2
		(345)	(7286)	(44633)		(2.8)
					OxM:	−150 (46)
6. B81						
Essex	66	121	−6680	–	S:	−42
Williams	69	(197)	(3286)			(6)
7. B82						
Forrest	74	−277	–	–	S:	−65
Williams	73	(28)				(20)
					M:	3.2 (1.1)
8. B83						
Corsoy	76	−134	−1362	–	M:	7.1
Williams	84	(93)	(863)			(2.3)
					OxM:	−133 (38)
9. I81 (WLS)	55	−223 (42)	–	–	–	
10. R81	72	−312 (19)	–	–	S:	−27 (3)

Table 4. (continued).

Crop Studies in model:	Intercept(s)	O	O^2	O^3	Other[b]	
SOYBEAN (continued)						
11. R82	46	2068 (919)	−48456 (20583)	289380 (138810)	–	
12. R83	54	−195 (57)	–	–	M:	18 (2)
13. R84	51	358 (288)	−6705 (2948)	–	M:	6.2 (1.6)
14. R86	61	1394 (461)	−31983 (9735)	191532 (62718)	M: OxM:	13.5 (3.1) −161 (53)
TOBACCO						
R83 [12.a]	6972	32023 (2724)	–	–	–	
TOMATO						
1. C81	61142	183876 (164176)	−3051897 (1437694)	–	S: Cov:	−24850 (17184) 0.56 (0.15)
2. C82	67581	−307158 (84990)	–	–	S:	−39762 (15874)
TURNIP						
1. R80 cv Just Right and Tokyo Cross [13.b] (WLS)						
Just Right	574	54817	−1239706	6779110	–	
Tokyo Cross	1009	(12910)	(267449)	(1609616)		
2. R80 cv Purple Top White Globe and Shogoin [13.a] (WLS)						
Purple Top	746	−4528	–	–	–	
Shogoin	614	(424)				
WHEAT						
1. A82 cv Abe:						
Abe	5024	16310 (14136)	−318943 (98733)	–	Cov:	32 (4)
2. A82 cv Arthur:						
Arthur	4704	−3577 (7916)	−127565 (53503)	–	Cov:	22 (2)

Table 4. (continued).

Crop Studies in model:	Intercept(s)	O	O^2	O^3	Other[b]
3. A82 cv Roland [14.e]					
Roland	5813	−32663 (2892)	–	–	Cov: 21 (5)
4. A83					
Abe	5493	34915	−405965	–	Cov:
Arthur	4630	(10216)	(88458)		Abe: 23.9 (4.5) Authur: 9.9 (4.6)
5. I82 [14.a]	8314	−142364 (17941)	735055 (140142)	–	–
6. I83 [14.c]	1057	223778 (121122)	−4381881 (2086418)	22671995 (10911538)	S: 236 (862)

[a] The ozone metric was the 7 h seasonal mean for barley, kidney bean, lettuce, peanut, sorghum, tomato, turnip, and wheat, and the 12 h seasonal mean for alfalfa, corn cotton, forage, soybean, and tobacco.

[b] S= the coefficient for seasonal sulfur dioxide metric, which was the 4 h seasonal mean (μL L^{-1}) for all studies except:
Alfalfa A84, where it was the sum of hourly exposures over the exposure period;
Forage I84 and I85, where it was the 24 h average for exposure days; and
Tomato C81 and C82, where it was the 7 h average.
M= 0 if water stressed
M= 1 if well-watered
M= 0.4662 if intermediate moisture (only for C85 cotton)
Cov= covariate (centered to mean zero).

[c] Analysis was conducted on square root transformed data.

Table 5. Parameter estimates for the Category I Weibull equations. Estimated approximate standard errors are shown in parentheses.[a] Figure references are in brackets for those equations represented in Figures 5-14.

Studies in model α label:	$\hat{\alpha}$	$\alpha(x)$ label:[b]	$\hat{\alpha}(x)$	$\hat{\omega}$	$\hat{\lambda}$
CROP					
ALFALFA					
1. C84	25922	M:	4175 (818)	0.187 (0.030)	1.57 (0.47)
2. C85	20614	M:	8792 (897)	0.177 (0.048)	1.91 (0.79)
3. A84 – no significant response, Weibull equation not fit					
BARLEY					
1. C82 – no significant response, Weibull equation not fit					
2. C83 – no significant response, Weibull equation not fit					
CORN[c]					
1. A81 [6.b]					
Pioneer 3780:	10750			0.108 (0.001)	4.34 (0.49)
PAG-397:	12755				
2. A85, cv Pioneer 3780 & LH74 × FR35 [6.d]					
Pioneer 3780:	11036	S:	1581 (3839)	0.139 (0.004)	3.27 (0.54)
LH74×FR35:	11791				
3. A85, cv FR20A × FR35 & FR20A × FR634 [6.f]					
FR20A×FR35:	12426	S:	−2902 (4912)	0.121 (0.003)	2.92 (0.35)
FR20A×FR634:	14736				
COTTON					
1. C81, M=1 [7.b]	14090			0.112 (0.003)	3.00 (0.48)
2. C81, M=0 [7.d]	8819			0.128 (0.020)	4.40 (3.17)
3. C82:	5104	M:	386 (340)	0.085 (0.004)	3.28 (0.84)
4. R82:	3364	S:	289 (474)	0.083 (0.002)	3.63 (0.54)
		T:	31 (152)		
5. R85, M=0 [7.f]	3360			0.112 (0.053)	4.07 (4.80)
6. R85, M=1	4106			0.081 (0.009)	3.31 (1.82)
7. C85 – no significant response, Weibull equation not fit.					
FORAGE					
1. I84	4170	S:	−13152 (32662)	0.083 (0.011)	2.98 (1.63)
		Cov:	4613 (1253)		
2. I85	1850	S:	−8527 (7705)	0.099 (0.120)	4.33 (12.0)
3. R84	10160	M:	1325 (247)	0.151 (0.026)	2.09 (0.74)
4. R85	7995	M:	1075 (454)	0.121 (0.016)	2.23 (1.20)
KIDNEY BEAN					
1. I80 [9.b]	2809			0.230 (0.032)	2.71 (0.89)
2. I82 [9.d]	2475			0.114 (0.005)	2.66 (0.61)
LETTUCE					
C83 [10.b]	60257			0.120 (0.004)	9.76 (3.45)
PEANUT					
R80 [10.d]	7428			0.109 (0.002)	2.27 (0.22)

Table 5. (continued)

CROP Studies in model α label:	$\hat{\alpha}$	$\alpha(x)$ label:[b]	$\hat{\alpha}(x)$	$\hat{\omega}$	$\hat{\lambda}$
SORGHUM					
A82 [10.f]	8157			0.314 (0.162)	2.07 (1.22)
SOYBEAN[c]					
1. A80	2830	Cov:	−242 (100)	0.088 (0.003)	2.47 (0.56)
2. A83SO$_2$					
Amsoy	2042	S:	−1019 (237)	0.083 (0.008)	3.98 (1.84)
Corsoy	1748				
3. A83cv (WLS)					
Amsoy	2057			0.108 (0.022)	1.75 (0.88)
Corsoy	2092				
Pella	2812				
Williams	2447				
4. A85	2637	M:	834 (166)	0.093 (0.021)	10.1 (12.5)
5. A86 M=0 [11.f]	3804			0.097 (0.005)	70.7 (155)
6. A86 M=1 [11.d]	5291			0.118 (0.013)	3.61 (1.58)
7. B81					
Essex	4494	S:	−5726 (856)	0.072 (0.009)	2.64 (0.79)
Williams	4841				
8. B82					
Forrest M=0	6661	S:	−10460 (3278)	0.101 (0.032)	0.67 (0.49)
Williams M=0	6061				
Forrest M=1	4966			0.083 (0.005)	3.17 (0.88)
Williams M=1	5218				
9. B83					
Corsoy M=0	5710			0.119 (0.010)	1.51 (0.45)
Williams M=0	6975				
Corsoy M=1	6043			0.092 (0.004)	1.75 (0.31)
Williams M=1	8158				
10. I81 (WLS)	2854			0.094 (0.014)	1.52 (0.87)
11. R81	5717	S:	−5096 (854)	0.084 (0.011)	0.98 (0.27)
12. R82	4951			0.086 (0.004)	2.77 (0.77)
13. R83	4929	M:	4998 (23412)	0.058 (0.740)	0.37 (1.94)
14. R84	3165	M:	833 (222)	0.086 (0.006)	3.33 (1.31)
15. R86	6712	M:	917 (274)	0.114 (0.009)	1.93 (0.52)
TOBACCO					
R83 [12.b]	6438			0.145 (0.009)	1.66 (0.40)
TOMATO					
1. C81	63735	S:	−23044 (18554)	0.154 (0.036)	3.06 (1.61)
		Cov:	0.59 (0.16)		
2. C82	63260	S:	−44837 (17771)	0.083 (0.026)	3.01 (1.97)

Table 5. (continued)

CROP Studies in model α label:	$\hat{\alpha}$	$\alpha(x)$ label:[b]	$\hat{\alpha}(x)$	$\hat{\omega}$	$\hat{\lambda}$
TURNIP (WLS)					
R80 [13.c]					
Just Right:	1209			0.093 (0.002)	2.70 (0.37)
Tokyo Cross:	1795				
Purple Top:	691				
Shogoin:	505				
WHEAT					
1. A82 cv Roland [14.f]	5446	Cov:	36.7 (5.1)	0.113 (0.005)	1.70 (0.30)
2. A82 cv Abe and Arthur [14.h]					
Abe:	5334	Cov:	38.0 (3.9)	0.143 (0.005)	2.52 (0.40)
Arthur:	4578	Cov:	24.9 (3.1)		
3. A83 [14.i]					
Abe:	6096	Cov:	26.0 (4.6)	0.116 (0.010)	7.95 (3.16)
Arthur:	5214	Cov:	7.5 (4.6)		
4. I82 [14.b]	8550			0.050 (0.004)	1.00 (0.00)
5. I83 [14.d]	4737	S:	−62 (1227)	0.115 (0.010)	1.94 (0.85)

[a] The ozone metric was the 7 h seasonal mean for barley, kidney bean, lettuce, peanut, sorghum, tomato, turnip, and wheat, and the 12 h seasonal mean for alfalfa, corn cotton, forage, soybean, and tobacco.

[b] S= the coefficient for seasonal sulfur dioxide metric, which was the 4 h seasonal mean (μL L^{-1}) for all studies except:
Alfalfa A84, where it was the sum of hourly exposures over the exposure period;
Forage I84 and I85, where it was the 24 h average for exposure days; and
Tomato C81 and C82, where it was the 7 h average.
M= 0 if water stressed
M= 1 if well-watered
M= 0.4662 if intermediate moisture (only for C85 cotton)
Cov= covariate (centered to mean zero).

[c] Analysis was conducted on square root transformed data but parameter estimates are on the original yield scale.

Table 6. Parameter estimates for the Category II polynomial equations. Standard errors of estimates are given in parentheses[a]. Figure references are in brackets for those equations represented in Figures 5-14[b].

Crop Studies in model: Intercept(s)		O	O^2	O^3	Other[c]	
ALFALFA						
C84, C85 [5.a]						
C84	25480	−63955	–	–	M84:	6402
C85	21683	(11544)				(1389)
					M85:	9678
						(1294)
					OxM84:	−49782
						(19391)
					OxM85:	−38777
						(20669)
BARLEY						
C82, C83 [5.d]						
C82	1.67	−1.42	–	–	M:	0.36
C83	1.76	(1.52)				(0.07)
CORN - no homogeneous combinations						
COTTON						
1. C81 M=1, C82 [7.a]						
C81	12703	46253	−1026111	–	M:	193
C82	4823	(18553)	(165638)			(289)
2. C81 M=0, C85 [7.c] (WLS)						
C81	6779	94442	−994519	–	M:	4910
C85	4140	(36279)	(288181)			(1535)
3. R82, R85 M=1 [7.g] (WLS)						
R82	3206	24581	−621858	–	T:	45
R85	3676	(10172)	(106115)			(97)
					S:	−2071
						(905)
					OxS:	44943
						(15314)
FORAGE						
R84, R85 [8.c]						
R84	11576	−47925	–	–	M:	1022
R85	9126	(4610)				(193)
KIDNEY BEAN - no homogeneous combinations						

Table 6. (continued)

Crop Studies in model: Intercept(s)		O	O^2	O^3	Other[c]	
SOYBEAN[d]						
1. A80, A83SO2, and A83cv Corsoy & Pella [11.a]						
A80	50	142	−3842	−	S:	−12
A83SO2 Amsoy	45	(87)	(967)			(2)
A83SO2 Corsoy	41				Cov:	−1.2
A83cv Corsoy	43					(0.9)
A83cv Pella	50					
2. A83cv Amsoy & Williams, A85, and A86 [11.c]						
A83cv Amsoy	29	153	−1707	−	M:	15
A83cv Williams	33	(97)	(867)			(3)
A85	48				OxM:	−150
A86	59					(44)
3. B81, B82, B83 and I81 (WLS) [11.e]						
B81 Essex	64	−73	−2103	−	S:	−46
B81 Williams	67	(59)	(577)			(6)
B82 Forrest	69				M:	5.4
B82 Williams	69					(1.6)
B83 Williams	83				OxM:	−77
B83 Corsoy	74					(29)
I81	51					
4. R81, R82 and R83 [11.g]						
R81	44	−134	−	−	M:	28
R82	49	(67)				(4)
R83	51				OxM:	−175
						(70)
					S:	−27
						(3)
5. R84 and R86 [11.i]						
R84	38	1358	−30477	177190	M:	12
R86	61	(421)	(8770)	(56731)		(3)
					OxM:	−132
						(49)
TOMATO						
C81, C82 [12.c]						
C81	69345	−183361	−	−	S:	−32672
C82	62530	(35479)				(12014)
					Cov:	0.56
						(0.15)

Table 6. (continued)

Crop Studies in model: Intercept(s)		O	O^2	O^3	Other[c]
WHEAT					
A82 (Abe & Arthur) and A83 [14.g]					
A82 Abe	4803	15897	−278349	–	Cov:
A82 Arthur	4273	(6659)	(47568)		A82 Abe: 29 (3)
A83 Abe	6117				A82 Arthur: 22 (3)
A83 Arthur	5258				A83 Abe: 22 (6)
					A83 Arthur: 7 (6)

[a] The ozone metric was the 7 h seasonal mean for barley, kidney bean, lettuce, peanut, sorghum, tomato, turnip, and wheat, and the 12 h seasonal mean for alfalfa, corn cotton, forage, soybean, and tobacco.

[b] Lettuce, Peanut, Sorghum, Tobacco, and Turnip were single studies, thus no Category II equations exist for these. See Table 4 for equations.

[c] S= the coefficient for seasonal sulfur dioxide metric, which was the 4 h seasonal mean (μL L^{-1}) for all studies except:

Alfalfa A84, where it was the sum of hourly exposures over the exposure period;

Forage I84 and I85, where it was the 24 h average for exposure days; and

Tomato C81 and C82, where it was the 7 h average.

M= 0 if water stressed

M= 1 if well-watered

M= 0.4662 if intermediate moisture (only for C85 cotton)

Cov= covariate (centered to mean zero).

[d] Analysis was conducted on square root transformed data.

Table 7. Parameter estimates for the Category II (homogeneous) Weibull equations. Estimated approximate standard errors are shown in parentheses[a]. Figure references are in brackets for those equations represented in Figures 5-14[b].

Studies in model α label:	$\hat{\alpha}$	α(x) label:[c]	$\hat{\alpha}(x)$	$\hat{\omega}$	$\hat{\lambda}$
CROP					
ALFALFA					
1. C84, C85 [5.b]					
C84:	25480	M84:	4108 (835)	0.179 (0.023)	1.78 (0.40)
C85:	20821	M85:	8884 (823)		
BARLEY - no significant response, Weibull equation not fit					
CORN - no homogeneous combinations					
COTTON (WLS)					
1. C82, R82, R85 M=1 [7.h]					
C82:	5073	S:	289 (388)	0.083 (0.002)	3.53 (0.39)
R82:	2987	T:	31 (125)		
R85, M=1:	3596	M:	388 (422)		
FORAGE					
1. I84, I85 [8.d]					
I84:	4069	S:	−9952 (9514)	0.085 (0.011)	3.10 (1.46)
I85:	2037	Cov:	4486 (1021)		
2. R84, R85 [8.e]					
R84:	10364	M:	1196 (250)	0.133 (0.015)	2.37 (0.74)
R85:	7440				
KIDNEY BEAN - no homogeneous combinations					
SOYBEAN[d]					
1. A80, A83SO2, A83cv Corsoy & Pella, R82, R84, R86 [11.b] (WLS)					
A80:	1793	S:	−1073 (240)	0.101 (0.004)	2.21 (0.32)
A83SO2, Amsoy:	1245	M:	882 (169)		
A83SO2, Corsoy:	938	Cov:	−144 (112)		
A83cv, Corsoy:	1141				
A83cv, Pella:	1836				
R82:	3839				
R84:	3190				
R86:	6931				
2. A83cv, Amsoy & Williams, A85, B82 M=0, B83 M=0 and R83 [11.h] (WLS)					
A83cv, Amsoy:	1122	M(A85):	1156 (381)	0.130 (0.010)	0.99 (0.29)
A83cv, Williams:	1560	M(R83):	2917 (349)		
A85:	3688	S:	−11636 (4130)		
B82, Forrest, M=0:	5481				
B82, Williams, M=0:	4998				

Table 7. (continued)

CROP Studies in model α label:	$\hat{\alpha}$	$\alpha(x)$ label:[c]	$\hat{\alpha}(x)$	$\hat{\omega}$	$\hat{\lambda}$
SOYBEAN (continued)					
2. A83cv, Amsoy & Williams, A85, B82 M=0, B83 M=0 and R83 [11.h] (WLS)					
B83, Williams, M=0:	7647				
B83, Corsoy, M=0:	6261				
R83:	2867				
3. B81, B82 M=1, B83 M=1, I81, R81 [11.j] (WLS)					
B81, Essex:	4606	S(B82&83):	−6251 (852)	0.092 (0.002)	1.72 (0.16)
B81, Williams:	4959	S(R81):	−4149 (491)		
B82, Forrest, M=1:	5279				
B82 Williams M=1:	5574				
B83, Williams, M=1:	8163				
B83 Corsoy M=1:	6049				
I81:	2775				
R81:	4604				
TOMATO					
C81, C82 [12.d]					
C81:	67417	S:	−36559 (13293)	0.204 (0.068)	1.67 (0.75)
C82:	59585	Cov:	0.61 (0.16)		
WHEAT - no homogeneous combinations					

[a] The ozone metric was the 7 h seasonal mean for barley, kidney bean, lettuce, peanut, sorghum, tomato, turnip, and wheat, and the 12 h seasonal mean for alfalfa, corn cotton, forage, soybean, and tobacco.

[b] Lettuce, Peanut, Sorghum, Tobacco, and Turnip were single studies, thus no Category II equations exist for these. See Table 4 for equations.

[c] S= the coefficient for seasonal sulfur dioxide metric, which was the 4 h seasonal mean (μL L^{-1}) for all studies except:

Alfalfa A84, where it was the sum of hourly exposures over the exposure period;

Forage I84 and I85, where it was the 24 h average for exposure days; and

Tomato C81 and C82, where it was the 7 h average.

M= 0 if water stressed

M= 1 if well-watered

M= 0.4662 if intermediate moisture (only for C85 cotton)

Cov= covariate (centered to mean zero).

[d] Analysis was conducted on square root transformed data but parameter estimates are on the original yield scale.

Table 8. Parameter estimates for the Category III polynomial equations[a]. Standard errors of estimateas are given in parentheses[b].

CROP Studies in model: Intercept(s)		O	O^2	O^3	Other[c]	
ALFALFA (WLS)						
A84	1395	−233	–	–	S:	−7
C84	21603	(1504)				(7)
C85	18401				M84:	10278
						(1462)
					M85:	12960
						(1402)
					OxM84:	−113504
						(19037)
					OxM85:	−102499
						(20936)
CORN[d] (WLS)						
A81 Pioneer	100	205	−4370	–	S:	−5
A81 PAG-397	109	(61)	(436)			(14)
A85 Pioneer	109					
A85 LH74xFR23	112					
A85 FR20AxFR634	116					
A85 FR20AxFR35	107					
COTTON (WLS)						
C81	9414	32871	−711290	–	M for:	
C82	4403	(9228)	(91536)		C81:	2530 (374)
C85	6396				C82:	206 (374)
R82	3053				C85:	4907 (1643)
R85	3507				R85:	5 (255)
					S:	−2234 (972)
					T:	48 (110)
					OxS:	
						47923 (16292)
FORAGE						
I84	2465	30960	−651530	–	M:	1030
I85	745	(14800)	(142175)			(188)
R84	9481				S:	−8785
R85	7019					(8841)
					Cov:	3788
						(875)
KIDNEY BEAN (WLS)						
I80	3210	−7972	–	–		
I82	2367	(1092)				
SOYBEAN[d] (WLS)						
A80	48	−61	−1691	–	S:	−20.7
A83SO2 Amsoy	45	(48)	(448)			(2.4)
A83SO2 Corsoy	42				Cov:	−2.3
A83cv Corsoy	42					(1.1)

Table 8. (continued)

CROP Studies in model: Intercept(s)		O	O^2	O^3	Other[c]	
SOYBEAN (continued)						
A83cv Pella	49				M:	7.9
A83cv Amsoy	42					(1.4)
A83cv Williams	45				OxM:	−57
A85	60					(23)
A86	72					
B81 Essex	58					
B81 Williams	61					
B82 Forrest	65					
B82 Williams	65					
B83 Williams	79					
B83 Corsoy	70					
I81	46					
R81	58					
R82	64					
R83	59					
R84	59					
R86	81					
TURNIP (WLS)						
Just Right	830	19829	−493650	2767201		
Purple Top	473	(7528)	(155958)	(938616)		
Shogoin	341					
Tokyo Cross	1265					
WHEAT (WLS)						
A82 Abe	5614	−8129	−137649	−	S:	−24
A82 Arthur	5085	(7871)	(57477)			(1145)
A82 Roland	4947				Cov:	Abe-82:28.8 (5.0)
A83 Abe	6997					Art-82: 22.9 (4.8)
A83 Arthur	6143					Rol-82: 20.3 (6.0)
I82	4076					Abe-83: 17.1 (7.0)
I83	4537					Art-83: 2.5 (7.3)

[a] The ozone metric was the 7 h seasonal mean for barley, kidney bean, lettuce, peanut, sorghum, tomato, turnip, and wheat, and the 12 h seasonal mean for alfalfa, corn cotton, forage, soybean, and tobacco.

[b] Lettuce, Peanut, Sorghum, and Tobacco were single studies (see Table 4). Barley and Tomato have Category III equations equivalent to their Category II equations (see Table 6).

[c] S= the coefficient for seasonal sulfur dioxide metric, which was the 4 h seasonal mean (μL L^{-1}) for all studies except:
Alfalfa A84, where it was the sum of hourly exposures over the exposure period; Tomato C81 and C82, where it was the 7 h average, and
Forage I84 and I85, where it was the 24 h average for exposure days.
M= 0 if water stressed; M=1 if well-watered;
M= 0.4662 if intermediate moisture (only for C85 cotton)
Cov= covariate (centered to mean zero).

[d] Analysis was conducted on square root transformed data.

Table 9. Parameter estimates for the Weibull "average" response to ozone for each species; Category III (heterogeneous) equations[a]. Estimated approximate standard errors are shown in parentheses.

CROP α label:	$\hat{\alpha}$	$\alpha(x)$ label:[b]	$\hat{\alpha}(x)$	$\hat{\omega}$	$\hat{\lambda}$
ALFALFA (WLS)					
A84:	1509	S:	7.5 (6.7)	0.178 (0.028)	2.07 (0.55)
C84:	24758	M, C84:	3987 (952)		
C85:	20297	M, C85:	8646 (933)		
BARLEY - no significant response, Weibull equation not fit					
CORN[c] (WLS)					
A81, Pioneer 3780:	10647	S:	−251 (3690)	0.124 (0.002)	2.83 (0.23)
A81, PAG-397:	12640				
A85, Pioneer 3780:	12246				
A85, LH74×FR23:	13069				
A85, FR20A×FR634:	14437				
A85, FR202×FR35:	12140				
COTTON (WLS)					
C81:	10924	M, C81:	4335 (692)	0.111 (0.005)	2.06 (0.33)
C82:	4835	M, C82:	347 (587)		
C85:	7050	M, C85:	6115 (2599)		
R82:	3221	M, R85:	116 (386)		
R85:	3849	S:	314 (541)		
		T:	58 (173)		
FORAGE					
I84:	2619	S:	−9818 (10114)	0.139 (0.015)	1.95 (0.56)
I85:	742	Cov:	4299 (1029)		
R84:	10726	M:	1232 (247)		
R85:	7712				
KIDNEY BEAN (WLS)					
I80:	3093			0.279 (0.079)	1.35 (0.70)
I82:	2178				
SOYBEAN[c] (WLS)					
A80:	1933	M:	920 (103)	0.107 (0.003)	1.58 (0.16)
A83SO2, Amsoy:	1593	S:	−1964 (256)		
A83SO2, Corsoy:	1272	Cov:	−186 (134)		
A83cv, Corsoy:	1238				
A83cv, Pella:	1979				
A83cv, Amsoy:	1201				
A83cv, Williams:	1604				
A85:	3519				
A86:	5435				
B81, Essex:	3322				
B81, Williams:	3667				
B82. Forrest:	4436				
B82, Williams:	4327				

Table 9. (continued).

CROP α label:	$\hat{\alpha}$	$\alpha(x)$ label:[b]	$\hat{\alpha}(x)$	$\hat{\omega}$	$\hat{\lambda}$
SOYBEAN (continued)					
B83, Williams:	7017				
B83, Corsoy:	5380				
I81:	1763				
R81:	3141				
R82:	4141				
R83:	3466				
R84:	3440				
R86:	7338				
WHEAT (WLS)					
A82, Abe:	5426	Cov82, Abe:	40.1 (7.8)	0.136 (0.006)	2.56 (0.41)
A82, Arthur:	4647	Cov82, Arthur:	25.4 (6.1)		
A82, Roland:	4553	Cov82, Roland:	28.8 (8.2)		
A83, Abe	6871	Cov83, Abe:	15.6 (8.7)		
A83, Arthur	5878	Cov83, Arthur:	2.8 (8.8)		
I82:	3643	S:	−57 (1502)		
I83:	4055				

[a] Lettuce, Peanut, Sorghum, Tobacco, and Turnip were single studies. See Table 4 for equations.

[b] S= the coefficient for seasonal sulfur dioxide metric, which was the 4 h seasonal mean (μL L^{-1}) for all studies except:

Alfalfa A84, where it was the sum of hourly exposures over the exposure period;

Forage I84 and I85, where it was the 24 h average for exposure days; and

Tomato C81 and C82, where it was the 7 h average.

M= 0 if water stressed

M= 1 if well-watered

Cov= covariate (centered to mean zero).

[c] Analysis was conducted on square root transformed data but parameter estimates are on the original yield scale.

Table 10. Residual sums of squares and degrees of freedom for the Category I polynomial and Weibull equations.

Crop	Study	Polynomial df	Polynomial RSS	Weibull df	Weibull RSS
ALFALFA					
	A84	35	1,284,964		no response
	C84	21	61,094,701	20	54,738,940
	C85	20	69,548,980	20	70,948,469
BARLEY					
	C82	22	0.53		no response
	C83	21	0.78		no response
CORN					
	A81	32	554	32	563
	A85 (cv P. & L.)	77	3,933	77	3,881
	A85 (cv F. & F.)	77	4,733	77	4,960
COTTON					
	C81 M=0	9	13466875	9	16045805
	C81 M=1	9	3770856	9	3679814
	C82	20	8634189	20	8104024
	C85	21	106974326		no response
	R82	19	668871	20	947531
	R85 M=0	8	739500	7	682247
	R85 M=1	8	2243037	7	1828742
FORAGE					
	I84	27	14,619,890	26	13,068,662
	I85	28	7,013,121	27	6,967,119
	R84	20	4,956,780	19	4,822,856
	R85	20	13,234,521	19	13,516,774
	R84 &85	20	24,973,375	19	25,813,459
KIDNEY BEAN					
	I80	10	200,225	10	215,809
	I82	14	813,920	14	666,458
LETTUCE		21	3,763,627,803	21	3,709,245,942
PEANUT		15	2,282,587	14	1,471,176
SORGHUM		16	2,696,714	15	2,557,600
SOYBEAN					
	A80	13	60	13	54
	A82SO2	27	268	27	284
	A82cv (WLS)	35	39	34	39
	A85	16	172	15	152
	A86	22	271	22	317
	B81	55	640	55	657
	B82	55	959	51	715

Table 10. (continued)

Crop	Study	Polynomial df	Polynomial RSS	Weibull df	Weibull RSS
SOYBEAN (continued)					
	B83	50	693	48	652
	I81 (WLS)	15	9.4	14	8.3
	R81	44	323	43	306
	R82	11	94	12	128
	R83	18	377	17	365
	R84	18	271	18	274
	R86	24	233	26	355
TOBACCO		20	2,488,415	19	2,450,006
TOMATO					
	C81	24	1,062,525,191	24	1,072,862,268
	C82	27	1,141,606,848	26	1,101,754,855
TURNIP (WLS)					
	JR & TC	29	28.1		
	S & PTWG	31	45.6		
	All cultivars			62	65.3
WHEAT					
	A82 Abe	13	2,077,830		
	A82 Arthur	13	749,429		
	A82 Abe & Arthur			28	2,998,362
	A82 Roland	14	2,951,448	13	1,227,211
	A83	14	881,776	14	880,432
	I82	14	2,841,844	15	2,551,703
	I83	34	17,648,464	35	19,538,951

Table 11. Residual sums of squares and degrees of freedom for the Category II polynomial and Weibull equations.

Crop	Study	Polynomial df	Polynomial RSS	Weibull df	Weibull RSS
ALFALFA					
	C84 & C85	41	135,080,598	42	126,953,370
BARLEY					
	C82 & C83	44	1.3		no response
COTTON					
	C81 M=1 & C82	31	28.2		
	C81 M=0 & C85	31	40.8		
	R82 & R85 M=1	36	33.2		
	C82, R82 & R85 M=1			61	58.0
FORAGE					
	R84 & R85	42	18,733,223	41	20,556,237
	I84 & I85			56	20,719,703
SOYBEAN					
	A80, A83SO2 & A83cv C&P	60	523		
	A83cv A&W, A85, & A86	59	1105		
	B81, B82, B83 & I81 (WLS)	181	192		
	R81, R82 & R83	76	908		
	R84 & R86 (WLS)	45	524		
	A80, A83SO2, A83cv C&P, R82, R84 & R86			123	140
	A83cv A&W, A85, B82 M=0, B83 M=0 & R83 (WLS)			103	102
	B81, B82 M=1, B83 M=1, I81 & R81 (WLS)			168	160
TOMATO					
	C81 & C82	54	2,564,385,981	53	2,549,965,334
WHEAT					
	A82 Abe & Arthur & A83	44	5,379,373		

Table 12. Residual sums of squares and degrees of freedom for the Category III polynomial and Weibull equations.

Crop	Polynomial		Weibull	
	df	RSS	df	RSS
ALFALFA (WLS)	77	143	79	128
CORN (WLS)	191	259	191	268
COTTON (WLS)	103	157	104	247
FORAGE (WLS)	99	42,126,262	99	44,719,400
KIDNEY BEAN (WLS)	27	47	26	59
SOYBEAN (WLS)	437	660	438	666
TURNIP (WLS)	61	126	62	65
WHEAT (WLS)	112	260	112	313

Table 13. Wald confidence interval estimates (95%) of percentage yield loss from ozone relative to yield at $O_3 = 0.025\ \mu L\ L^{-1}$. These estimates are based on the Category I or II Weibull response equations for all crops except barley (which is based on the Category II polynomial equation).[1] Estimated losses are restricted to ozone levels within the dose levels of the experiments.

CROP Model[2]	Ozone ($\mu L\ L^{-1}$)							
	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
ALFALFA								
7.1	(0.4, 1.9)	(1.9, 5.8)	(4.3, 9.8)	(7.4, 13.9)	(11.2, 17.9)	(15.4, 22.2)	(19.5, 26.8)	(23.2, 32.1)
BARLEY								
M=0	(-0.5, 1.4)	(-1.5, 4.1)	(-2.6, 6.8)	(-3.6, 9.5)	(-4.6, 12.2)			
M=1	(-0.4, 1.1)	(-1.3, 3.4)	(-2.1, 5.6)	(-3.0, 7.8)	(-3.8, 10.1)			
CORN								
5.1	(0, 0.4)	(0.1, 2.2)	(1.0, 5.6)	(3.5, 11.1)	(8.8, 19.0)	(17.9, 29.3)	(31.1, 41.3)	(47.0, 54.8)
5.2	(0.1, 1.3)	(1.0, 4.8)	(2.9, 9.8)	(6.3, 16.1)	(11.6, 23.5)	(18.7, 31.5)	(27.5, 40.0)	(37.5, 48.8)
5.3	(-0.1, 0.7)	(-0.1, 2.7)	(0.3, 5.8)	(1.6, 10.0)	(4.1, 15.2)	(8.2, 21.2)	(14.0, 27.8)	(21.7, 34.9)
COTTON								
5.1	(0, 1.6)	(0.6, 6.2)	(2.6, 12.2)	(6.9, 19.5)	(13.7, 27.6)	(23.1, 36.2)	(34.0, 45.4)	(44.6, 55.8)
5.2	(-0.6, 0.8)	(-2.9, 3.9)	(-6.2, 9.2)	(-10.0, 16.9)	(-12.6, 26.0)	(-11.5, 35.1)	(-4.5, 42.6)	(7.3, 49.8)
7.1	(0.6, 2.0)	(3.5, 8.4)	(10.2, 17.8)	(21.8, 30.1)	(37.3, 44.8)	(52.8, 62.1)		
5.5	(-1.9, 2.4)	(-6.9, 9.5)	(-11.5, 18.4)	(-11.3, 26.1)	(-3.6, 30.8)			
FORAGE								
7.1	(-1.2, 4.6)	(-0.9, 15.2)	(5.4, 26.0)	(17.6, 36.8)				
7.2	(-0.2, 2.3)	(0.2, 7.4)	(2.3, 13.0)	(6.3, 18.6)	(12.2, 24.1)	(19.3, 29.8)	(26.0, 37.1)	
KIDNEY BEAN								
5.1	(-0.3, 0.6)	(-0.8, 2.1)	(-1.3, 4.0)	(-1.6, 6.4)	(-1.6, 9.0)	(-1.1, 11.8)	(0.0, 14.7)	(1.9, 17.6)
5.2	(-0.3, 2.5)	(-0.2, 8.7)	(1.5, 16.2)	(5.5, 24.3)	(12.0, 32.6)	(20.8, 40.8)	(31.1, 48.9)	(41.3, 57.5)
LETTUCE								
	(0.0, 0.0)	(0.0, 0.0)	(-0.1, 0.1)	(-0.5, 0.7)	(-1.6, 2.6)	(-3.9, 7.8)	(-6.8, 18.9)	(-6.0, 38.0)
PEANUT								
	(0.9, 2.6)	(4.0, 8.9)	(8.7, 16.3)	(15.2, 24.4)	(23.0, 32.8)	(31.9, 41.3)	(41.2, 49.8)	(50.2, 58.1)
SORGHUM								
	(-0.5, 1.0)	(-1.3, 3.0)	(-1.7, 5.1)	(-1.9, 7.3)	(-1.5, 9.3)	(-0.7, 11.2)	(0.6, 12.9)	(2.4, 14.6)
SOYBEAN								
7.1	(1.3, 3.2)	(5.5, 10.5)	(12.0, 18.6)	(20.4, 27.2)	(29.7, 36.3)	(38.7, 46.4)		
7.2	(2.7, 4.9)	(8.8, 13.2)	(15.0, 20.2)	(20.7, 26.7)	(25.7, 33.0)	(29.8, 39.4)	(33.3, 45.6)	
7.3	(3.1, 4.5)	(10.6, 14.0)	(19.4, 23.6)	(28.7, 33.2)	(37.6, 42.8)	(45.9, 52.3)	(53.3, 61.2)	
5.6	(-0.7, 1.4)	(-2.4, 5.7)	(-3.6, 11.8)	(-2.9, 19.0)	(1.2, 26.6)	(9.6, 33.8)	(20.5, 42.2)	
5.5	(0.0, 0.0)	(0.0, 0.0)	(0.0, 0.0)	(0.0, 0.0)	(0.0, 0.0)	(0.0, 0.0)	(-6.5, 7.3)	
TOBACCO								
	(0.0, 3.8)	(1.3, 11.1)	(4.2, 18.0)	(8.4, 24.3)	(13.6, 30.0)	(19.6, 35.2)	(25.8, 40.3)	(31.6, 45.6)

Table 13 (continued)

CROP Model[2]	Ozone (μL L^{-1})							
	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
TOMATO								
	(-0.1, 2.2)	(0.4, 6.6)	(2.0, 10.6)	(4.5, 14.4)	(7.4, 18.3)	(10.4, 22.5)	(12.8, 27.5)	(14.5, 33.4)
TURNIP								
	(0.7, 3.0)	(3.9, 10.5)	(9.9, 19.8)	(18.9, 30.1)	(30.4, 41.0)	(42.9, 52.3)	(54.5, 64.2)	
WHEAT								
5.1	(1.2, 4.4)	(4.9, 13.2)	(10.2, 21.8)	(16.9, 29.8)	(24.5, 37.2)	(32.4, 44.2)	(40.1, 50.9)	(47.2, 57.5)
5.2	(0.1, 1.4)	(0.7, 4.8)	(2.3, 9.2)	(4.9, 14.1)	(8.9, 19.6)	(14.1, 25.3)	(20.6, 31.3)	(27.8, 37.4)
5.3	(0.0, 0.0)	(-0.1, 0.1)	(-0.4, 0.6)	(-1.1, 2.1)	(-1.9, 5.4)	(-1.0, 11.0)	(6.3, 18.1)	
5.4	(6.2, 12.9)	(19.7, 32.2)	(32.8, 45.9)	(44.4, 56.4)	(53.7, 65.0)	(60.9, 72.6)	(66.3, 79.2)	(70.6, 84.8)
5.5	(-1.0, 5.4)	(-1.2, 16.1)	(1.6, 25.8)	(7.1, 34.3)	(14.9, 41.5)	(24.0, 47.9)	(32.9, 54.3)	(40.0, 62.2)

[1] No Weibull equation was fit to barley. For both corn and soybean, the analysis was based on the square root scale but percentage losses are expressed on the original scale.

[2] Model refers to the Table number and equation number for the crop (e.g., alfalfa equation 7.1 refers to Table 7, alfalfa equation 1. Barley yield loss is based on the homogeneous Category II polynomial barley equation in Table 6.

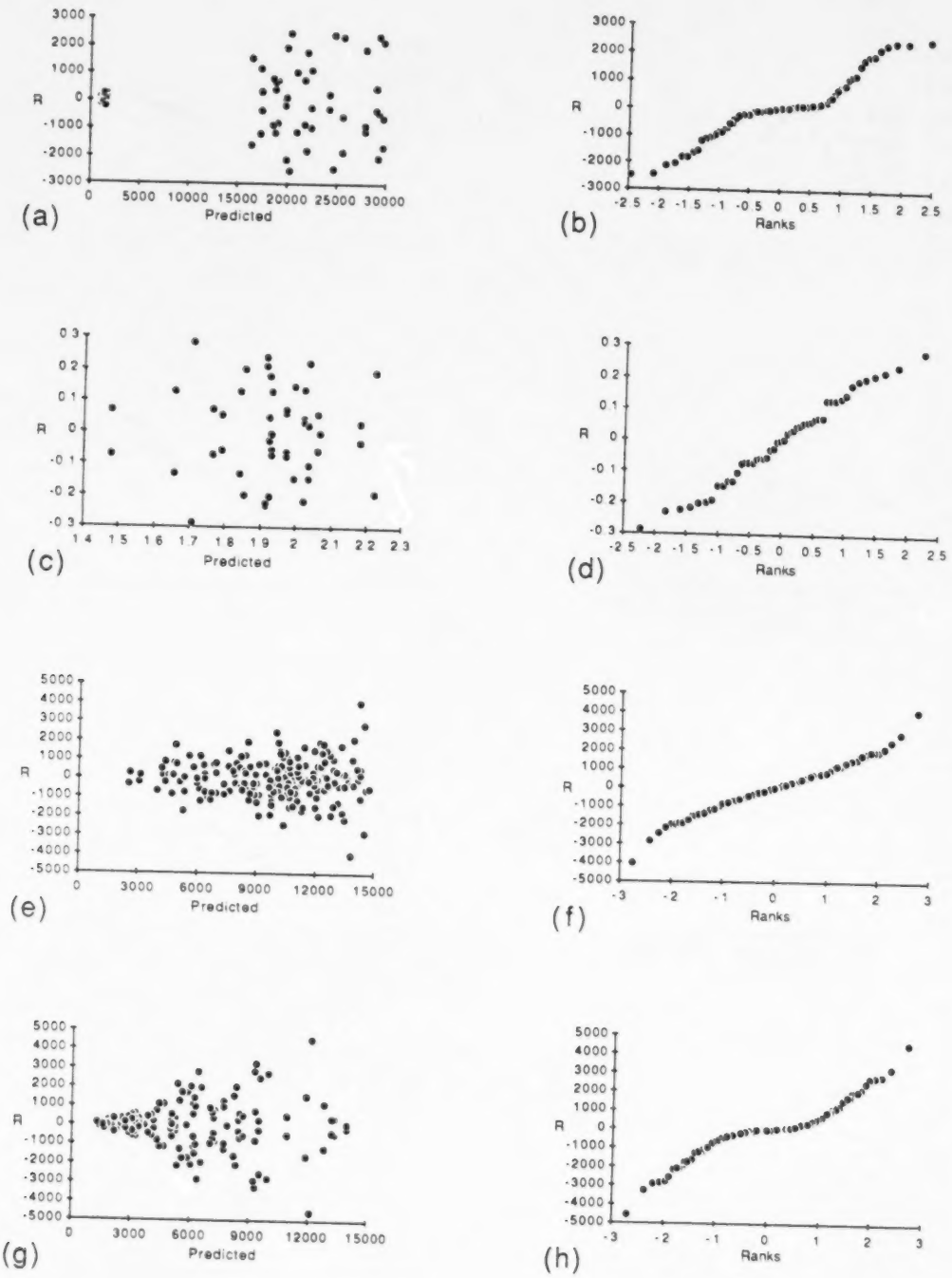

Figure 1: Residuals from ordinary least squares analyses of variance versus predicted yield and ranked normal scores for: alfalfa (a-b), barley (c-d), corn (e-f), cotton (g-h).

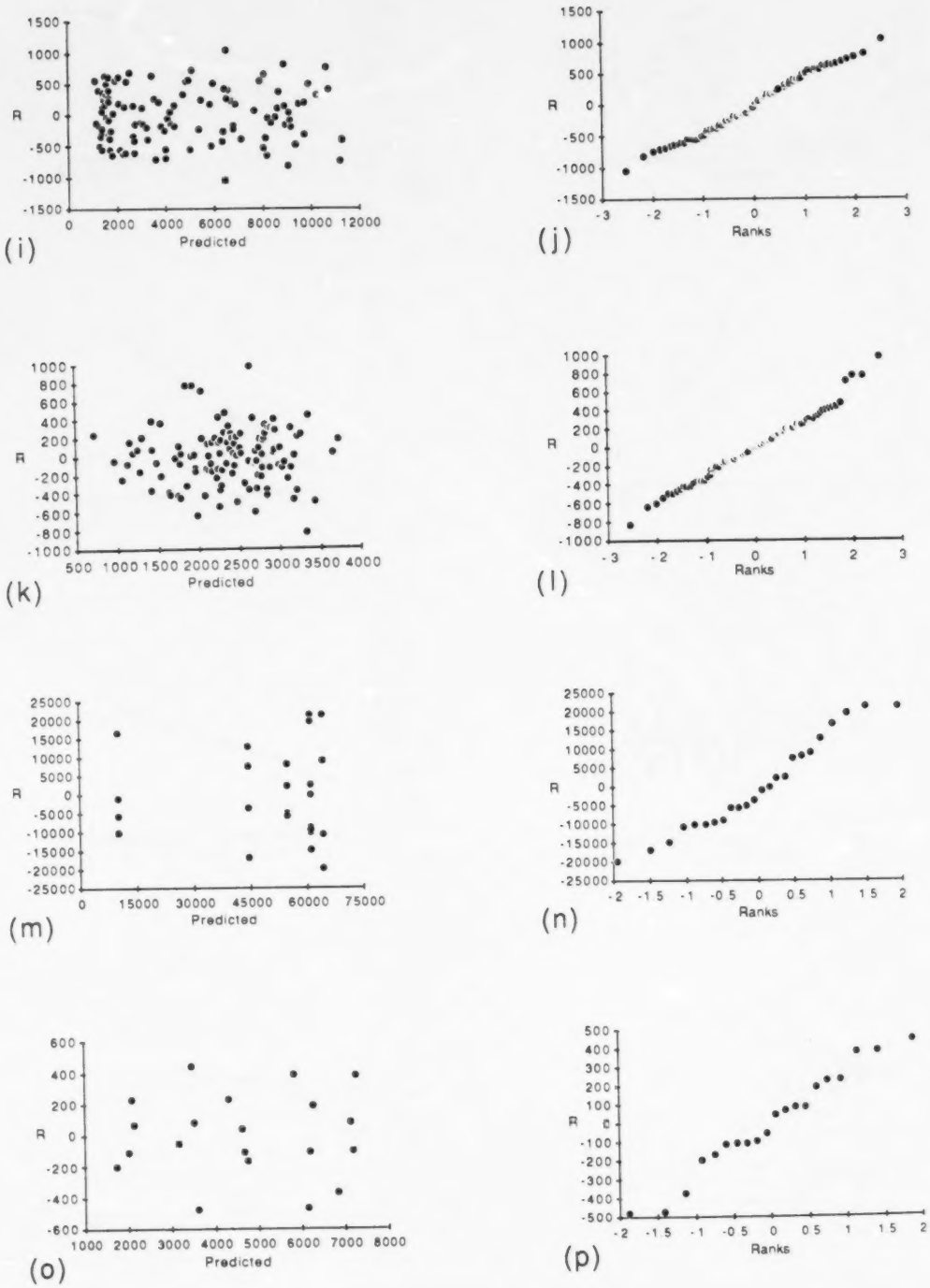

Figure 1 continued: Residuals from ordinary least squares analyses of variance versus predicted yield and ranked normal scores for: forage (i-j), kidney bean (k-l), lettuce (m-n), peanut (o-p).

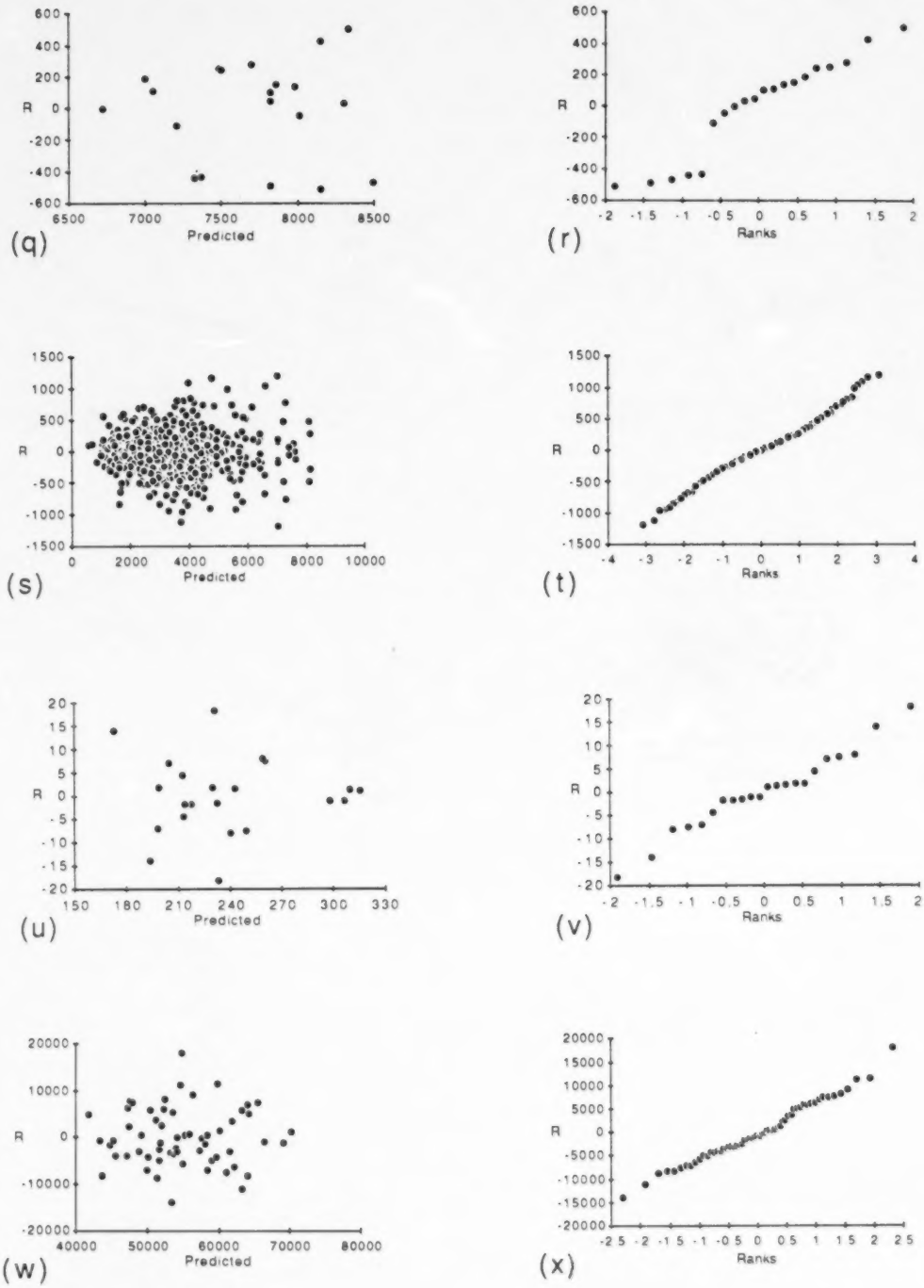

Figure 1 continued: Residuals from ordinary least squares analyses of variance versus predicted yield and ranked normal scores for: sorghum (q-r), soybean (s-t), tobacco (u-v), tomato (w-x).

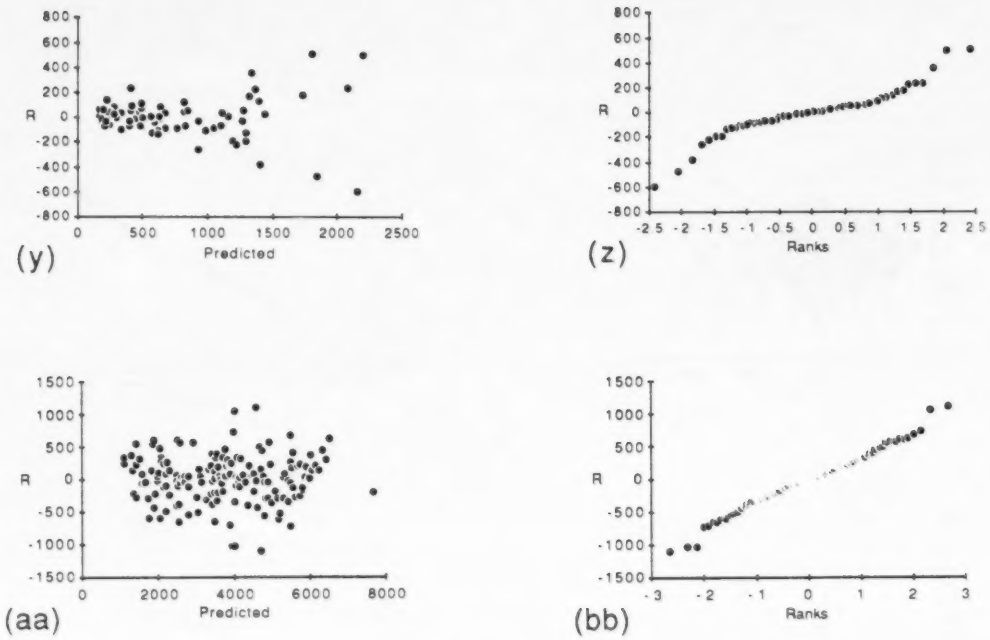

Figure 1 continued: Residuals from ordinary least squares analyses of variance versus predicted yield and ranked normal scores for: turnip (y-z) and wheat (aa-bb).

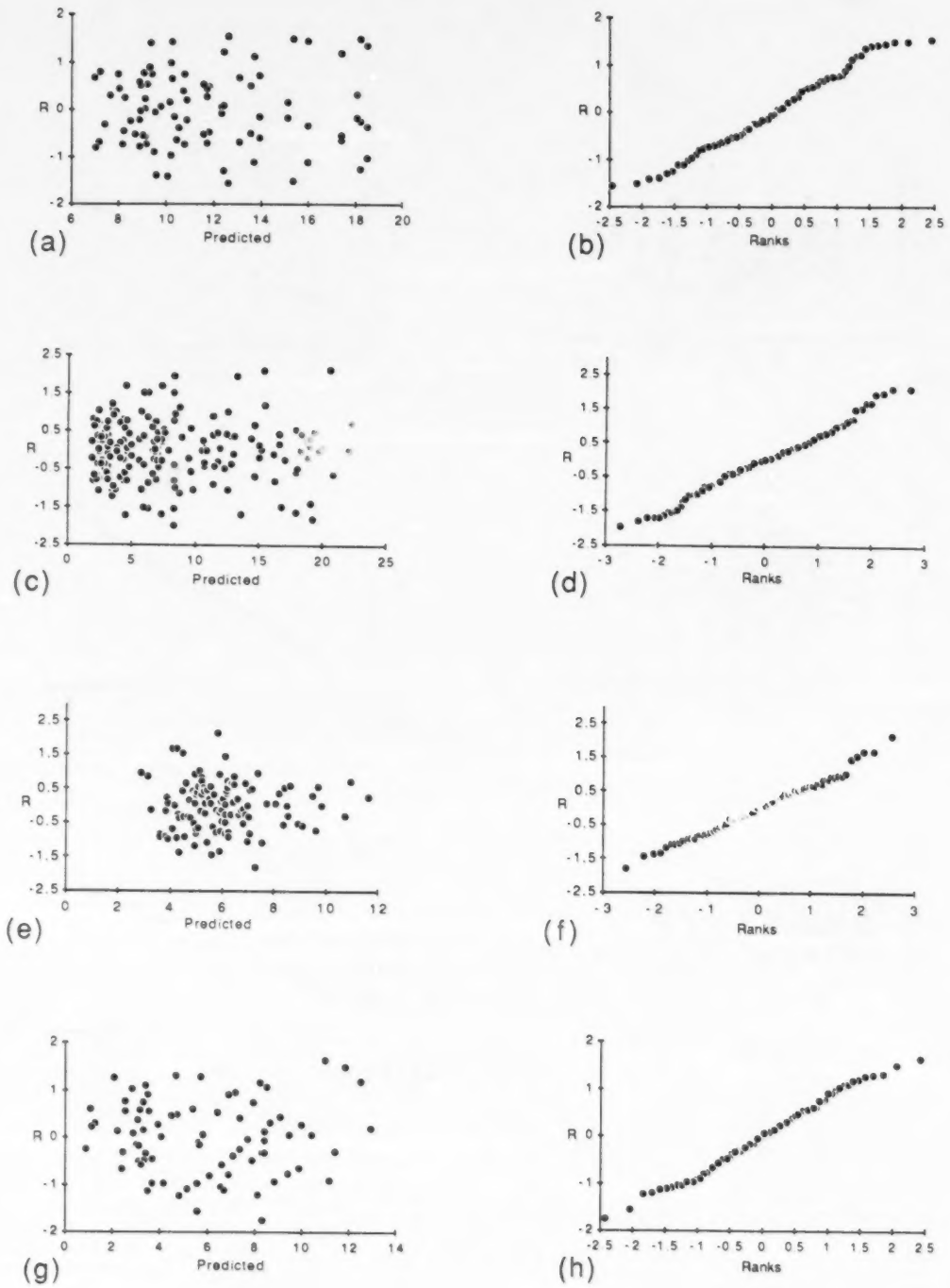

Figure 2: Residuals from weighted least squares analyses of variance versus predicted yield and ranked normal scores for: alfalfa (a-b), cotton (c-d), kidney bean (e-f), turnip (g-h).

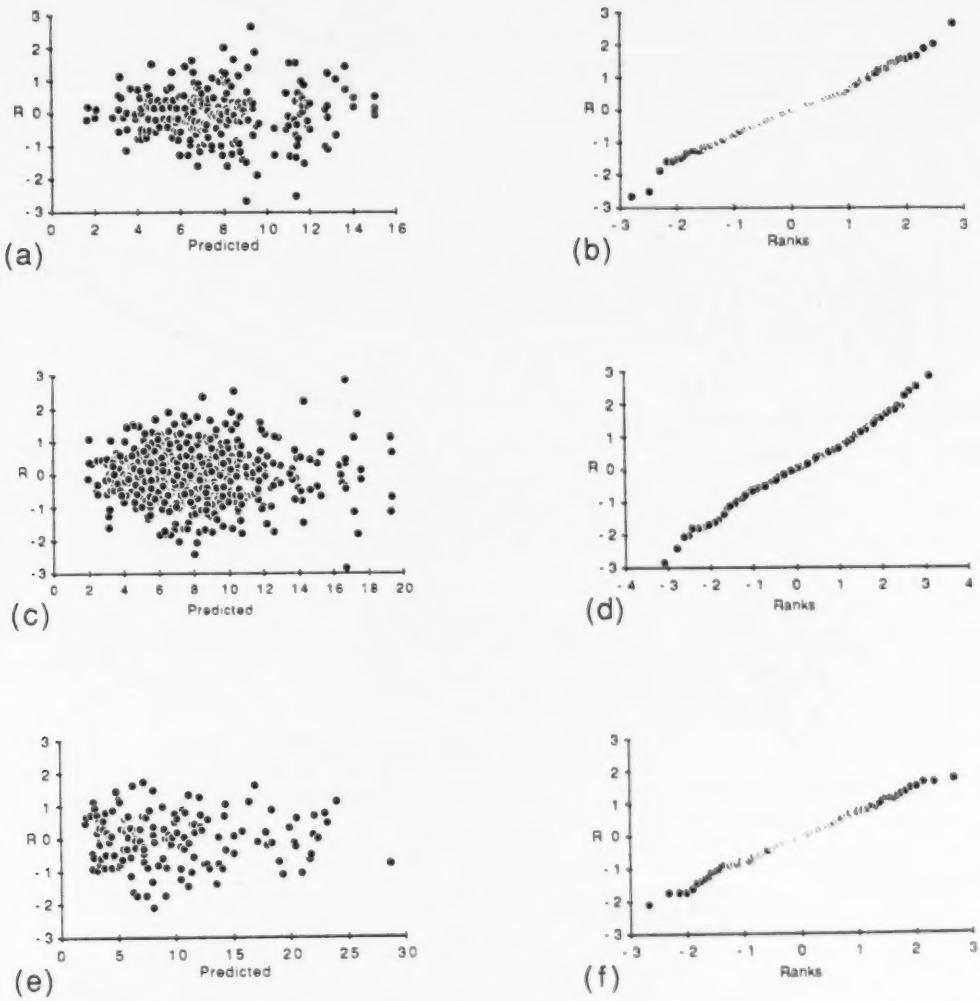

Figure 3: Residuals from weighted least squares analyses of variance versus predicted yield and rank normal scores for: corn (a-b), soybean (c-d), and wheat (e-f).

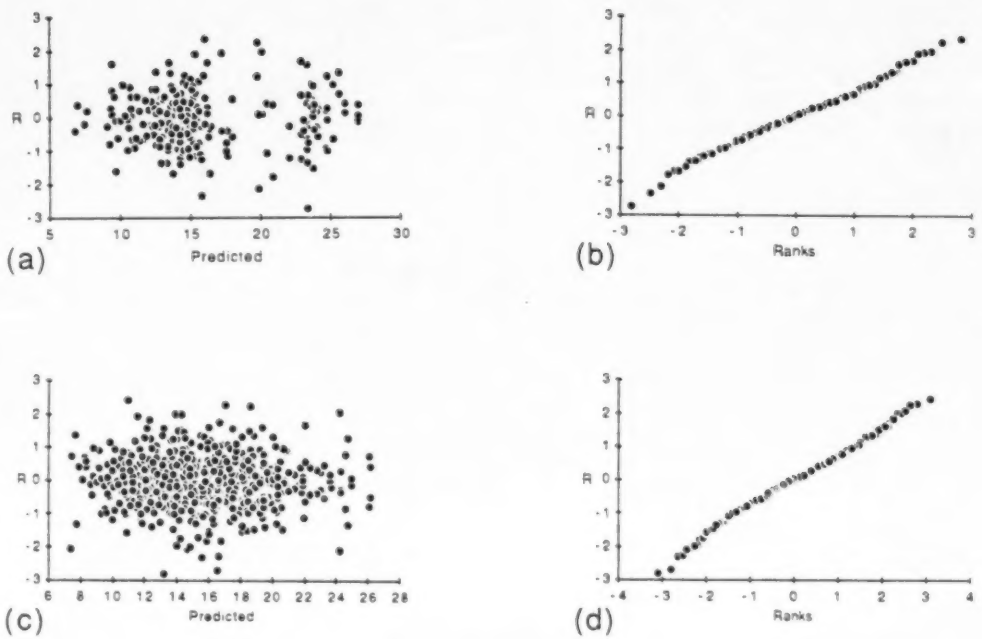

Figure 4: Residuals from weighted least squares analyses of variance using the square root transformation of yield versus predicted yield and ranked normal scores for: corn (a-b), and soybean (c-d).

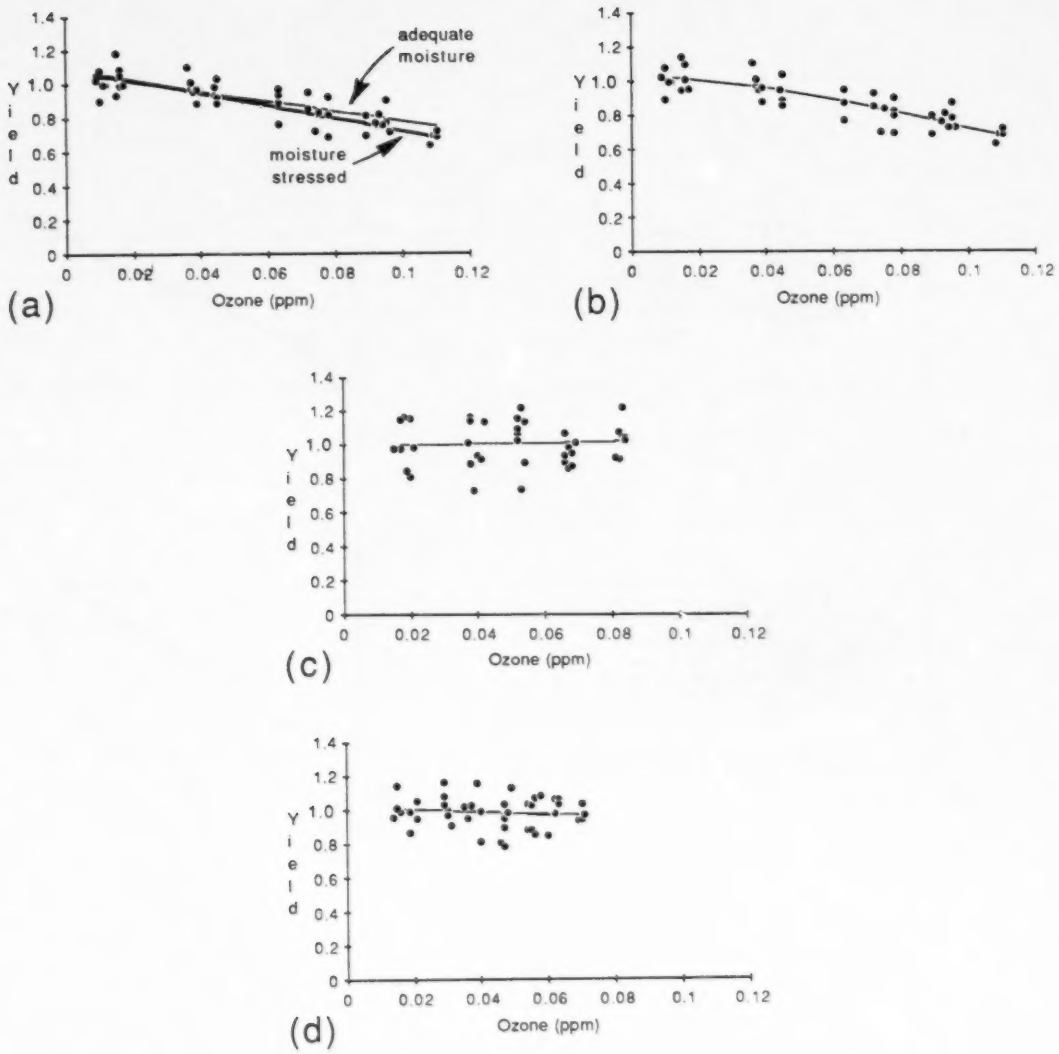

Figure 5: Plots of relative yield responses to ozone from: **a**) polynomial equation of C84 and C85 alfalfa, **b**) Weibull equation of C84 and C85 alfalfa, **c**) polynomial equation of A84 alfalfa (no significant response), and **d**) polynomial equation of C82 and C83 barley (no significant response).

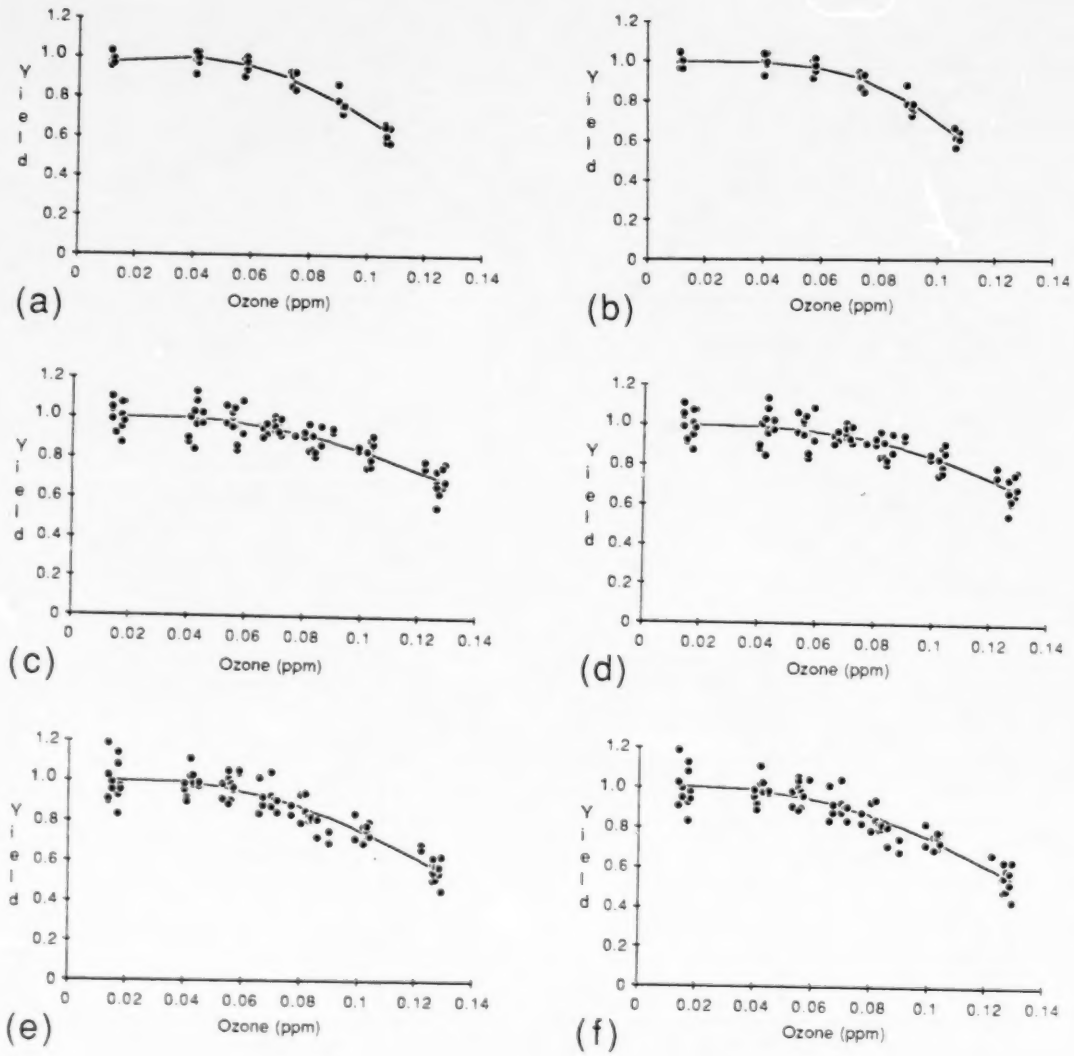

Figure 6: Plots of relative yield responses of corn to ozone from: a) polynomial equation of A81-cultivars *Pioneer 3780* and *PAG 397*, b) Weibull equation of A81-cultivars *Pioneer 3780* and *PAG 397*, c) polynomial equation of A85-cultivars *Pioneer 3780* and *LH74xFR23*, d) Weibull equation of A85-cultivars *Pioneer 3780* and *LH74xFR23*, e) polynomial equation of A85-cultivar *FR20AxFR35* and *FR20AxFR634*, f) Weibull equation of A85-cultivar *Fr20AxFR35* and *FR20AxFR634*.

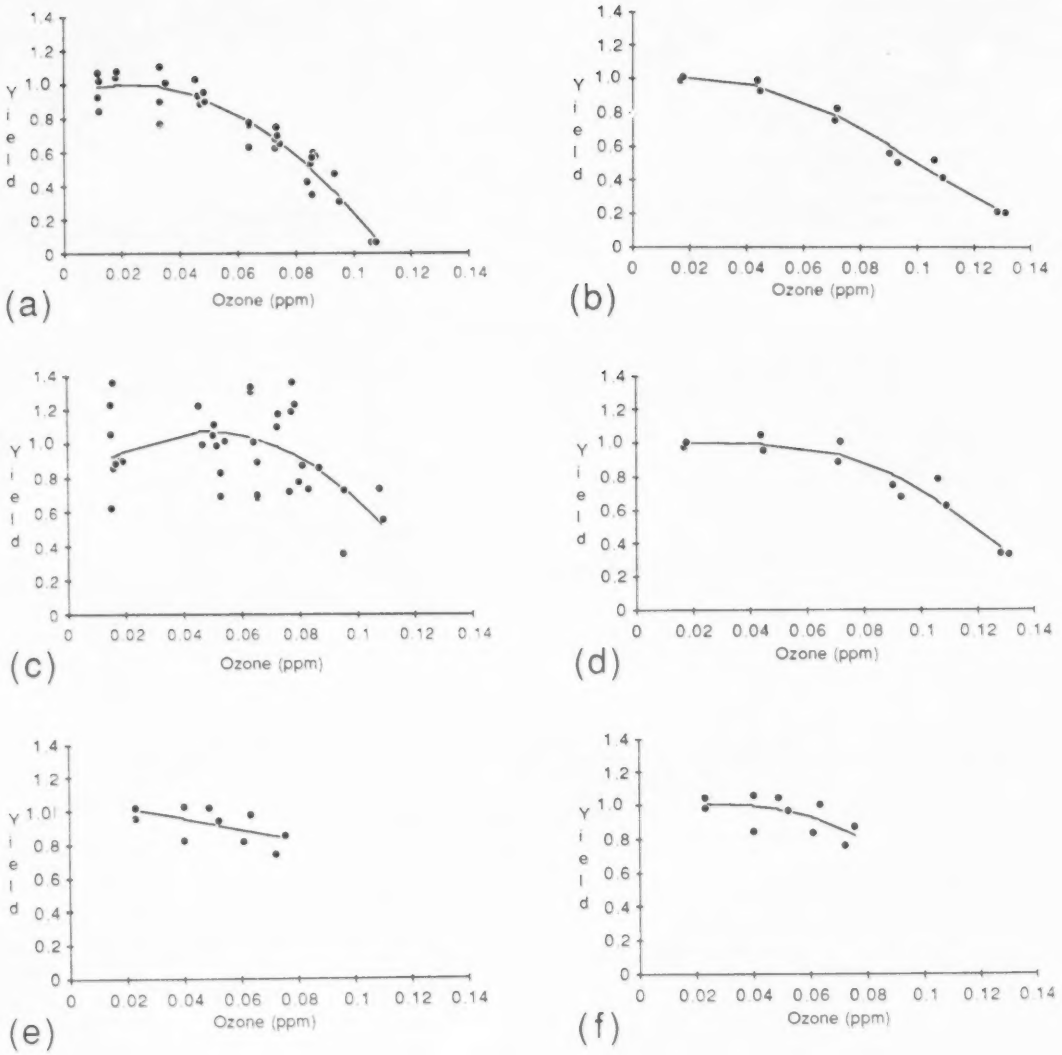

Figure 7: Plots of relative yield responses of cotton to ozone from: a) polynomial equation of C81(M=1) and C82, b) Weibull equation of C81(M=1), c) polynomial equation of C81(M=0) and C85 d) Weibull equation of C81(M=0), e) polynomial equation of R85(M=0), f) Weibull equation of R85(M=0).

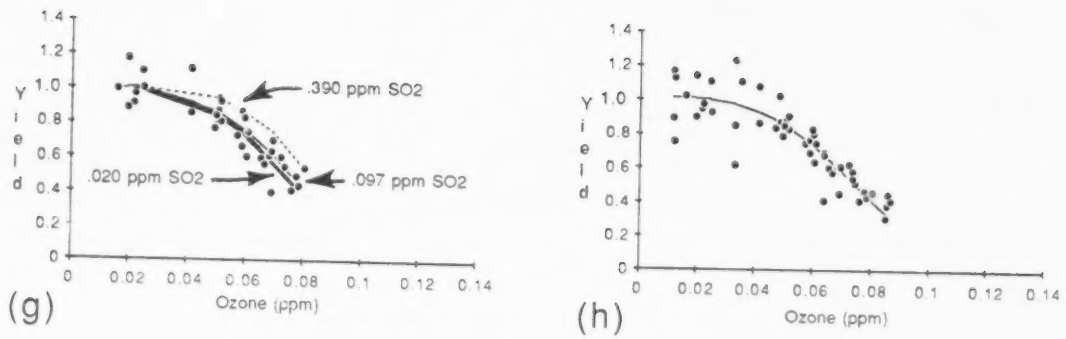

Figure 7 continued: Plots of relative yield responses of cotton to ozone from: g) polynomial equation of R82, R85(M=1), h) Weibull equation of C82, R82, and R85(M=1).

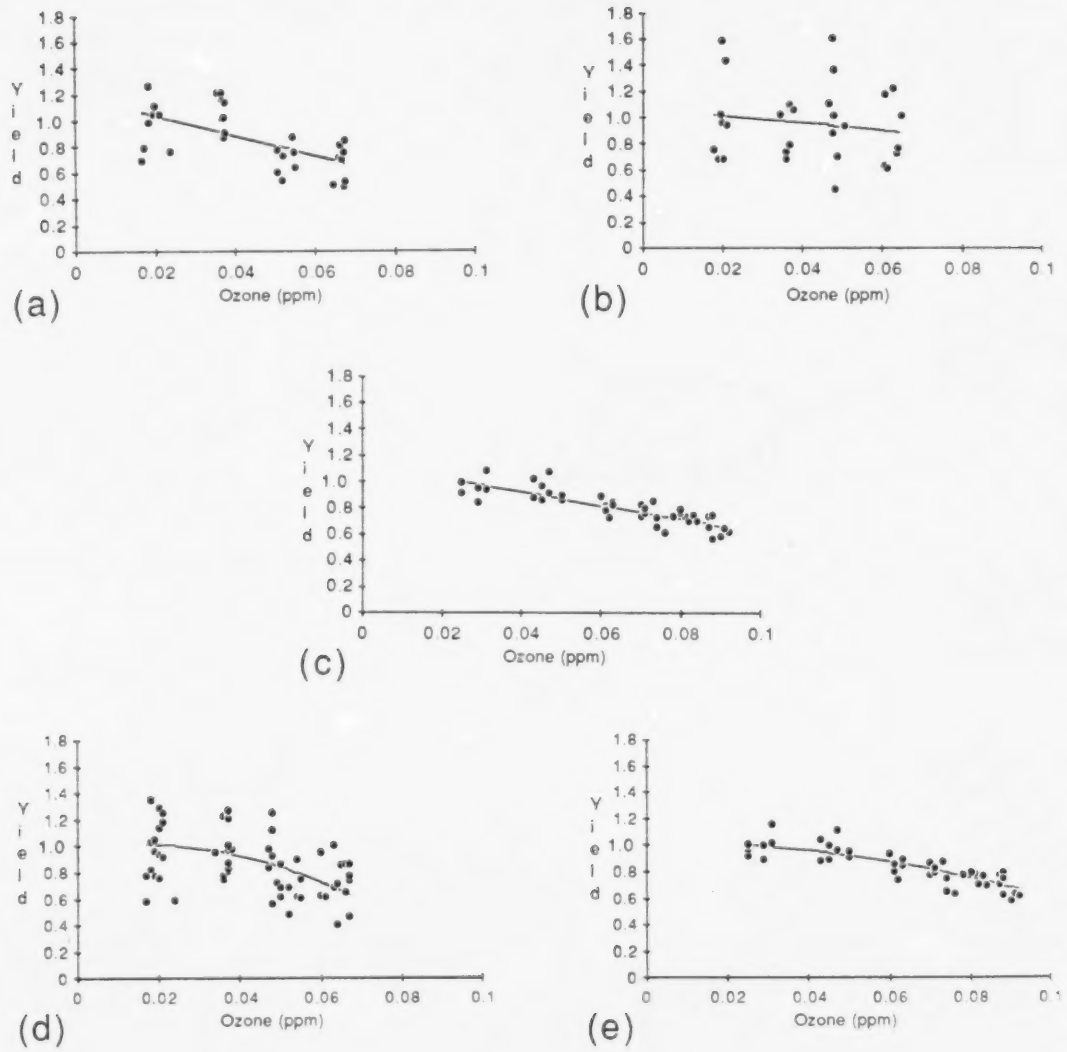

Figure 8: Plots of relative yield response of forage to ozone from: a) polynomial equation of I84, b) polynomial equation of I85, c) polynomial equation of R84 and R85, d) Weibull equation of I84 and I85, and e) Weibull equation of R84 and R85.

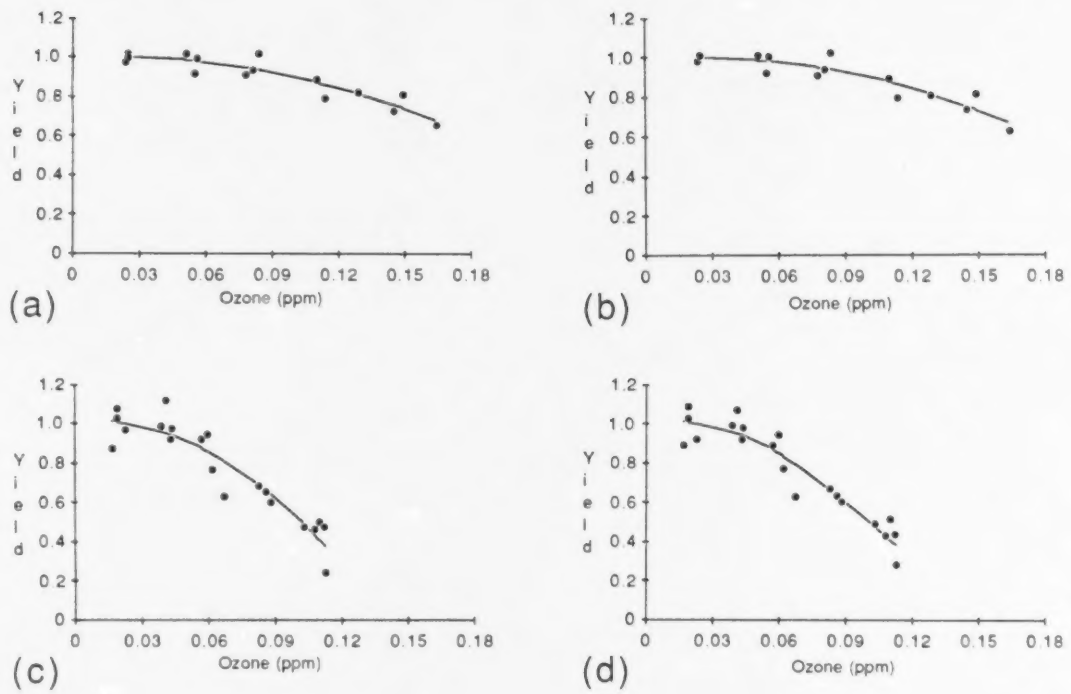

Figure 9: Plots of relative yield response of kidney bean to ozone from: **a**) polynomial equation of I80, b) Weibull equation of I80, c) polynomial equation of I82, and **d**) Weibull equation of I82.

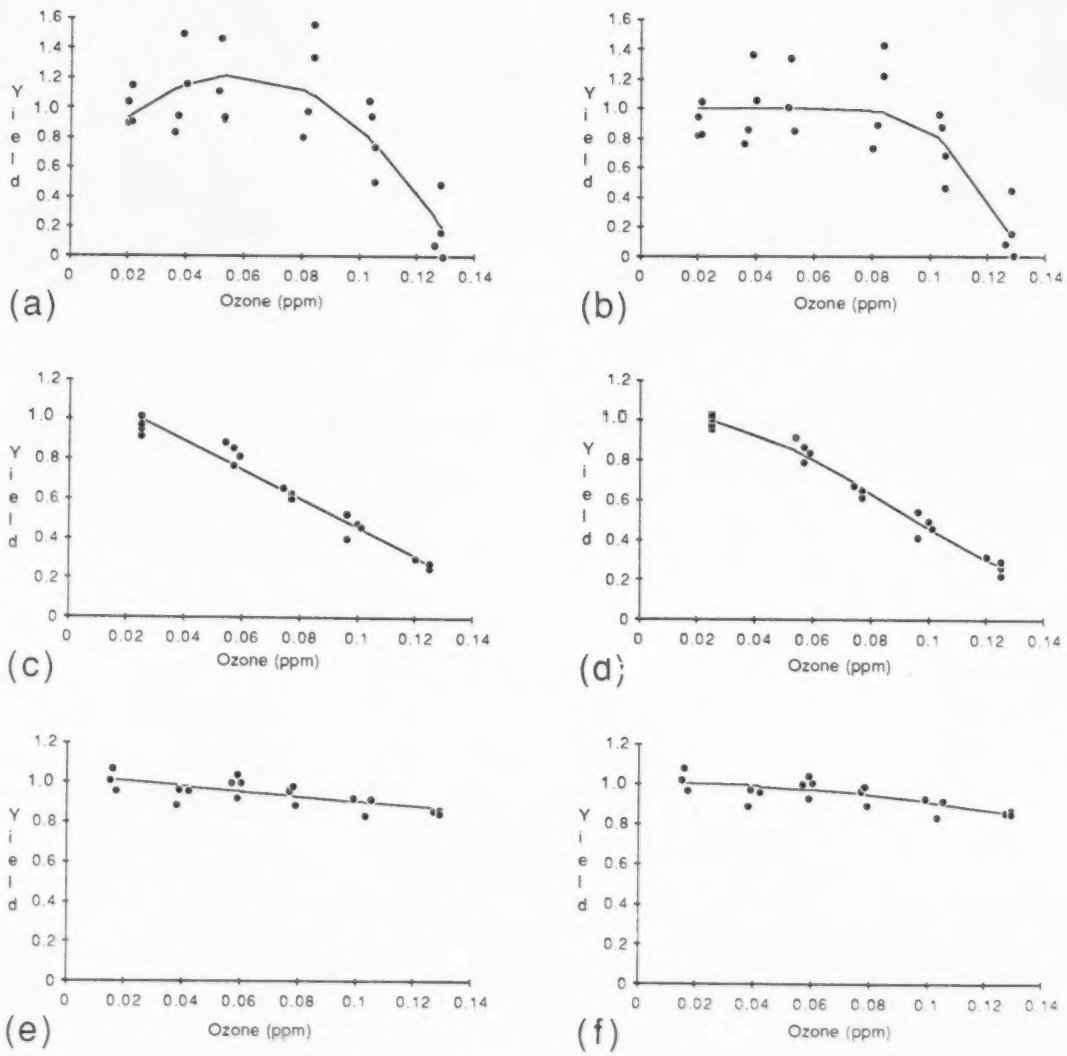

Figure 10: Plots of relative yield response to ozone from: a) polynomial equation of C83 lettuce, b) Weibull euqation of C83 lettuce, c) polynomial equation of R80 peanut, d) Weibull equation of R80 peanut, e) polynomial equation of A80 sorghum, and f) Weibull equation of A80 sorghum.

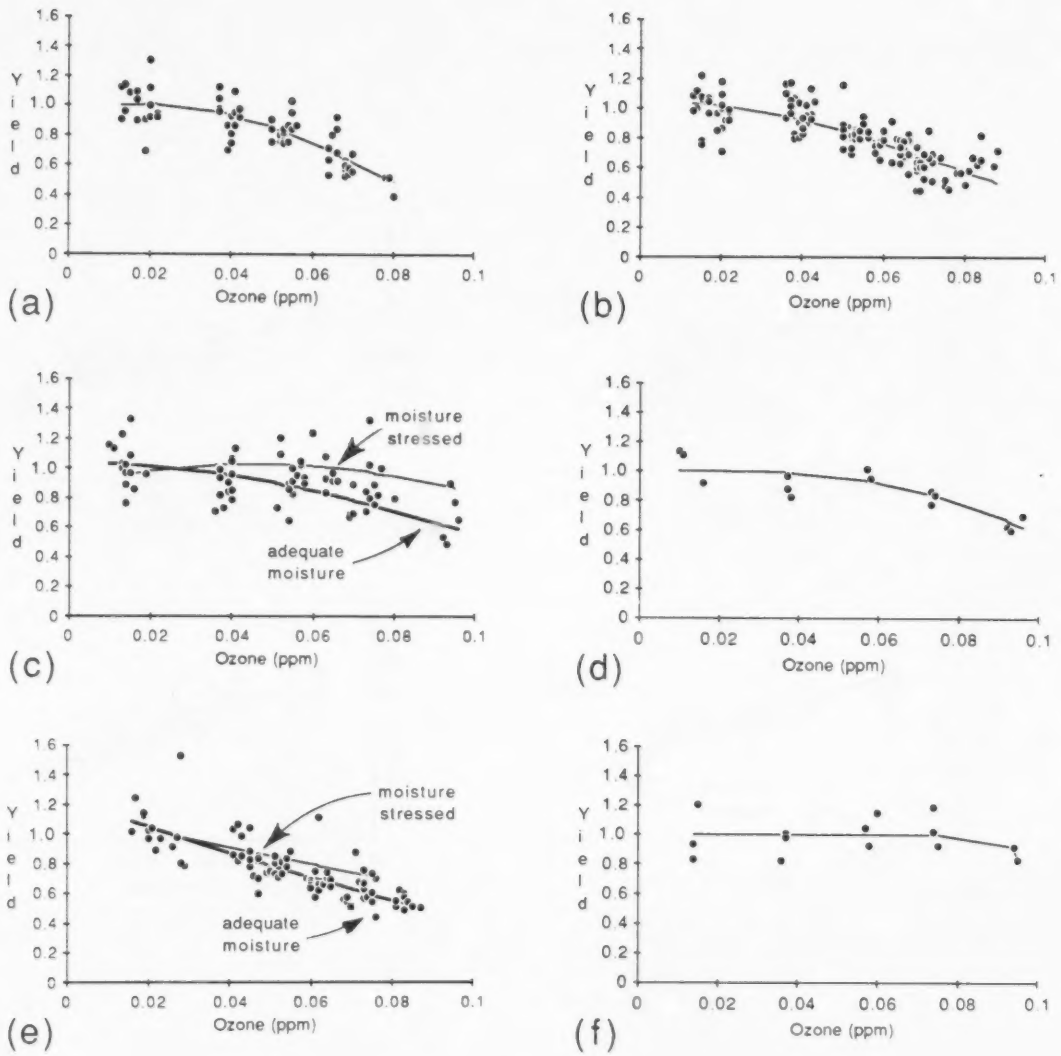

Figure 11: Plots of relative yield response of soybean to ozone from: a) polynomial equation of A80, A83cv-cultivars *Corsoy* and *Pella*, and A83SO2, b) Weibull equation of A80, A83SO2, A83cv-cultivars *Corsoy* and *Pella*, R82, R84 and R86, c) polynomial equation of A83cv-cultivars *Amsoy* and *Williams*, A85, and A86, d) Weibull equation of A86(M=1), e) polynomial equation of B81, B82, B83, and I81, f) Weibull equation of A86(M=0).

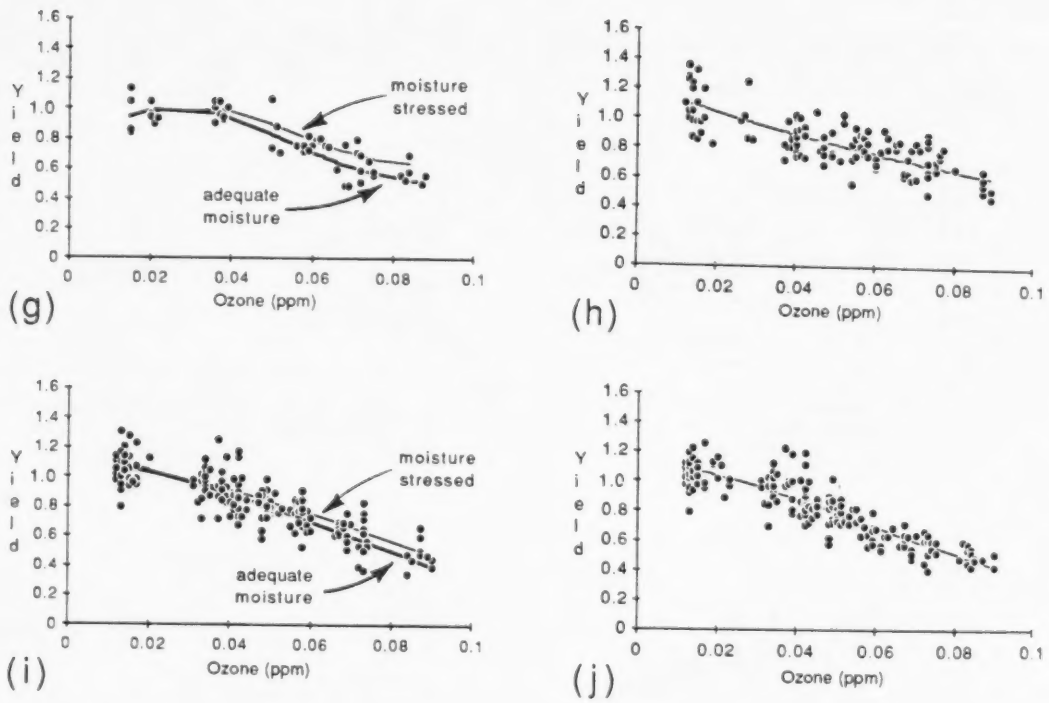

Figure 11 continued: Plots of relative yield response of soybean to ozone from: g) polynomial equations of R81, R82, and R83, h) Weibull equation of A83cv-cultivars *Amsoy* and *Williams*, A85, B82(M=0), B83(M=0), and R83, i) polynomial equation of R84 and R86, and j) Weibull equation of B81, B82(M=1), B83(M=1), R81, and I81.

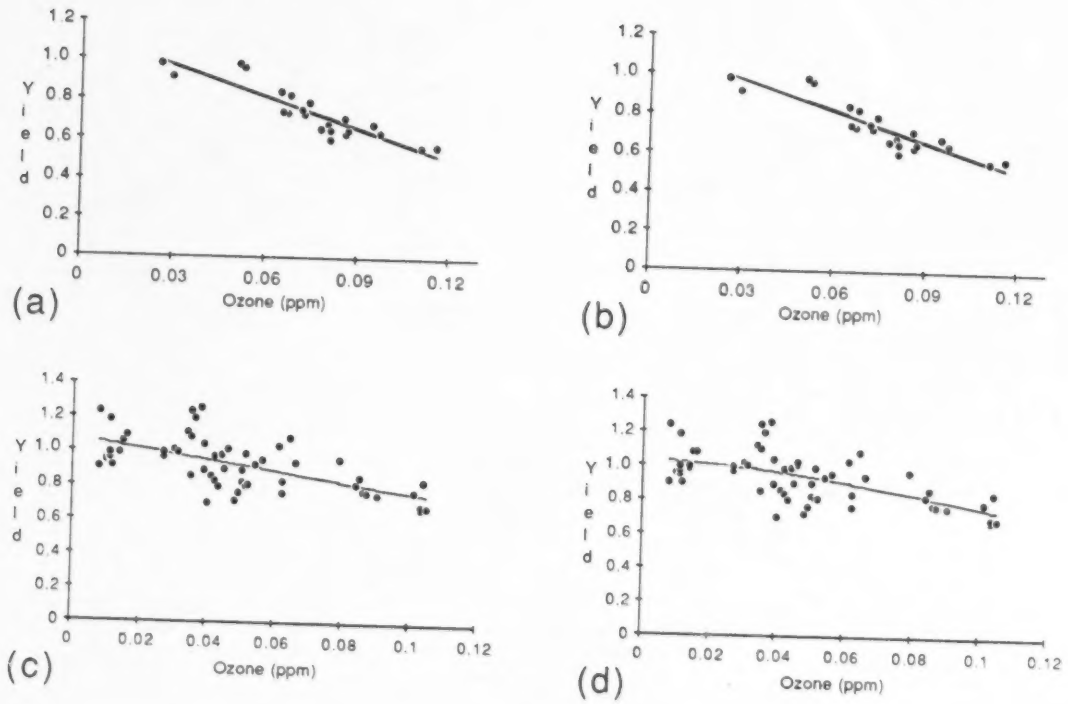

Figure 12: Plots of relative response to ozone from: a) polynomial equation of R83 tobacco, b) Weibull equation of R83 tobacco, c) polynomial equation of C81 and C82 tomato, and d) Weibull equation of C81 and C82 tomato.

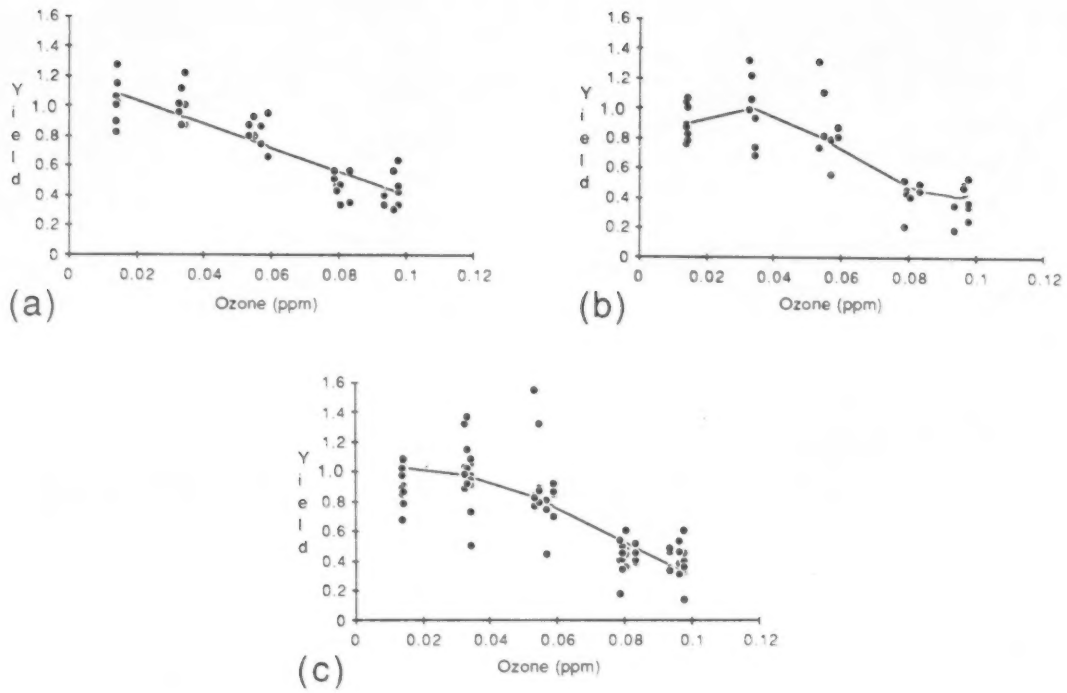

Figure 13: Plots of relative yield response of R80 turnip to ozone from: a) polynomial equation of cultivars *Shogoin'* and *Purple Top White Globe*, b) polynomial equation of cultivars *Just Right* and *Tokyo Cross*, and c) Weibull equation of all four cultivars.

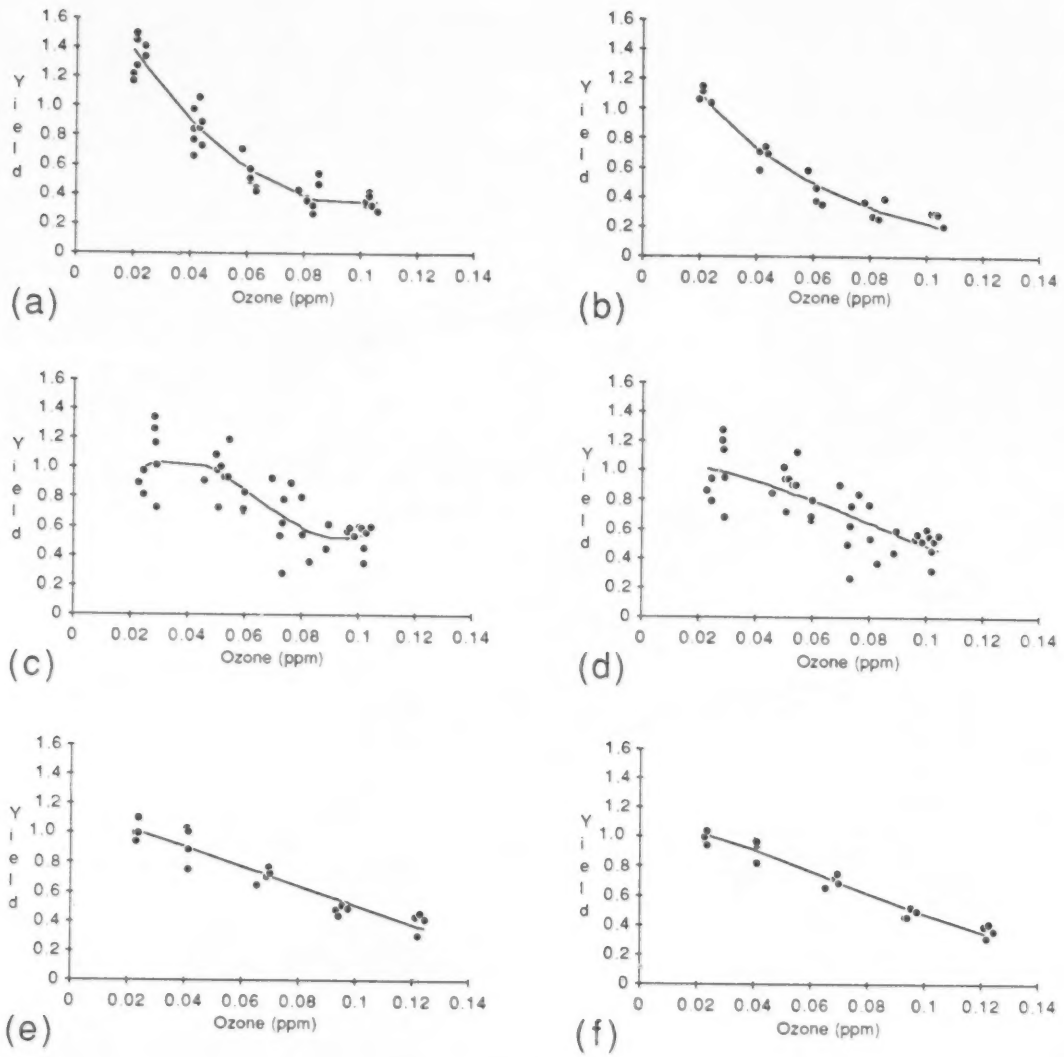

Figure 14: Plots of relative yield responses of wheat to ozone from: a) polynomial equation of I82, b) Weibull equation of I82, c) polynomial equation of I83, d) Weibull equation of I83, e) polynomial equation of A82-cultivar *Roland*, f) Weibull equation of A82-cultivar *Roland*.

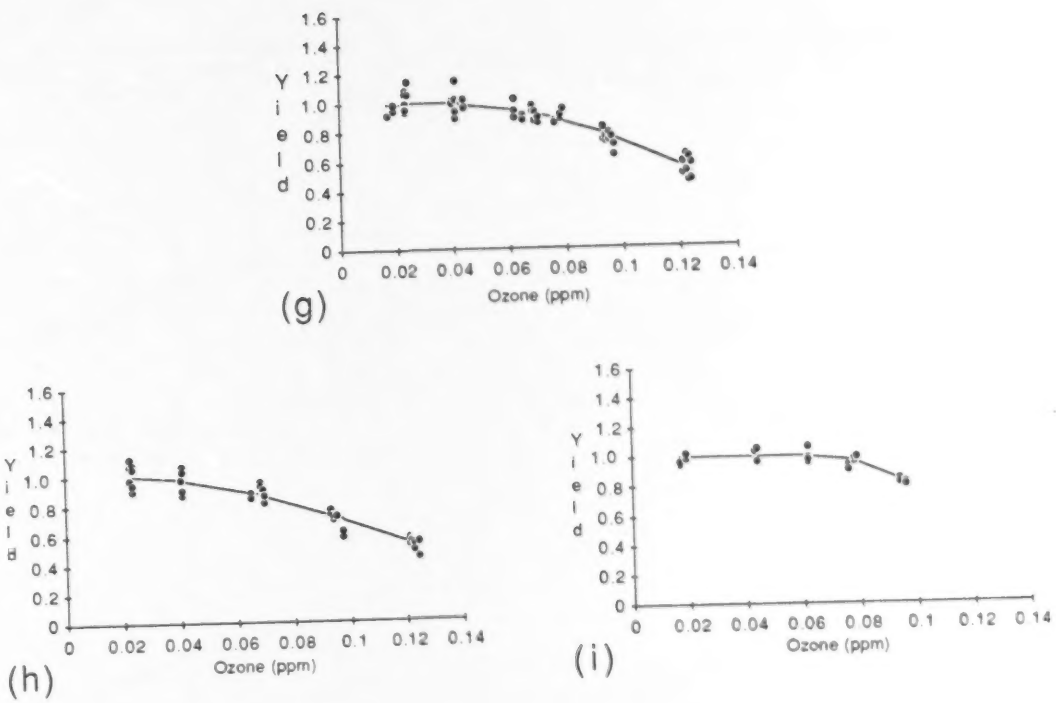

Figure 14 continued: Plots of relative yield response of wheat to ozone from: g) polynomial equations of A82-cultivars *Abe* and *Arthur-71* and A83, h) Weibull equation of A82-cultivars *Abe* and *Arthur-71*, i) Weibull equation of A83.